Edge Computing for Enterprises 2019

Abstract: **This report provides a comprehensive analysis of trends in Edge Computing as it relates to Private LTE/5G networks. The report covers market trends and technology development in edge computing in key 5G markets. The report explores key use cases driving the market as well as evolving dynamic amongst the communication service providers, hyperscale cloud providers, and enterprises. The report includes edge compute revenue forecasts and spending on hardware and services.**

Kyung Mun

July 2019

MOBILE EXPERTS

Edge Computing for Enterprises 2019

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MEXP-EDGEPLTE-19
July 2019

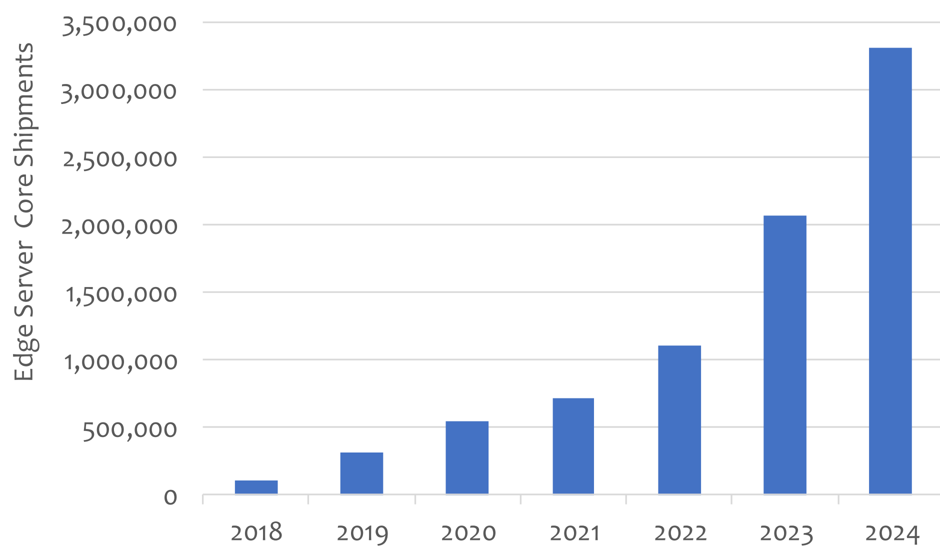
1 EXECUTIVE SUMMARY

Cloud computing has truly taken a "bite" out of traditional enterprise networking. By virtualizing computing and storage hardware and providing API calls, the cloud providers have enabled a new IT consumption model for enterprises. Instead of buying hardware and software resources, deploying and managing them, the cloud providers have enabled the enterprises, and developers of software applications, to access the underlying IT assets as a service. Telco operators see an opportunity to replicate this playbook, not only for their Telco network services, but also enable new revenue generation from third-party applications that require distributed cloud infrastructure for a variety of cost, performance, and regulatory reasons.

Edge computing infrastructure investments are driven from two vectors:

1. Operators see opportunities to run Telco workloads such as vRAN and other Telco workloads on containerized microservices to make their network services more efficient and agile. Besides the cost savings and operational efficiency, the operators see new revenue generation opportunities from enterprise use cases that can benefit from lower latency and reduced data transport as they transition to 5G.
2. Cloud service players also see opportunity to securely and more efficiently deliver cloud services and service increasing enterprise demand for hybrid cloud services whereby they can utilize the public cloud services through on-premise data centers closer to them.

While the traditional CDN use case represents the biggest segment for edge cloud services, new use cases such as private LTE/5G, cloud gaming, and others are driving investment towards Near Edge "micro" data centers, and Far Edge and On-Prem facilities. While the Near Edge data centers will dominate shipment of edge computing hardware servers, the Far Edge and On-Prem facilities will increasingly account for edge computing hardware deployments. Overall, the edge computing server shipments will grow at over 50% CAGR from about 6,000 in 2018 to over 74,000 in 2024, representing over 3M CPU and GPU cores in 2024.



Source: Mobile Experts

Chart 1: Edge Computing Server Core Shipment

Translating the edge compute server investment in dollar terms, the total edge computing CAPEX spend on hardware equipment and software and services will grow from about $240M in 2018 to just under $2B in 2024 – over 40% CAGR growth. The hardware portion will represent about 52% of that spend in 2024 and the rest in software and services. As the edge computing trend expands from centralized hyperscale data centers to distributed edge cloud nodes, the CAPEX spend on Near Edge data centers will represent the largest segment.

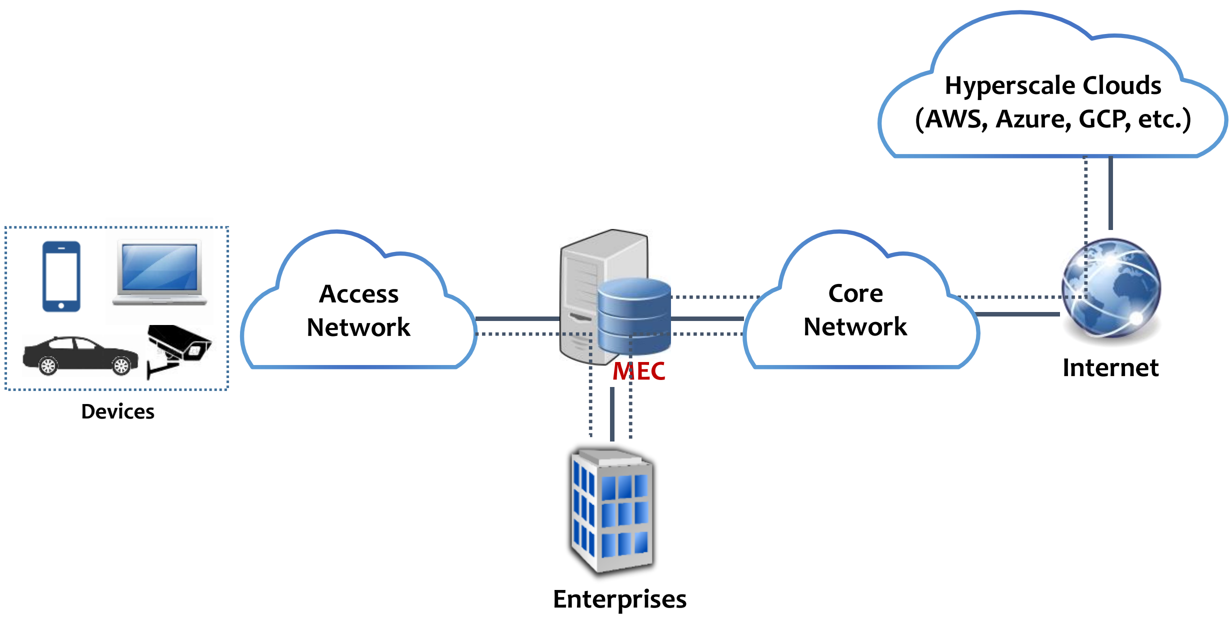
Edge computing represents a convergence point for Telco and cloud service providers to enable new enterprise applications with faster and more responsive (5G) network capabilities along with more distributed cloud computing environments. The business model around "who/what/how" between the Telcos, cloud providers, and neutral infrastructure providers is still evolving as well as the fragmented ecosystem of open source initiatives and standards such as CNCF, OpenStack, LF Edge, ETSI MEC, etc. The edge computing market represents a convergence point for two major technology trends today: 5G and cloud computing. Evolving market and technology dynamics will offer very quick growth in the near term.

2 WHAT IS EDGE COMPUTING?

Edge Computing is the latest "cool" technology that has brought excitement to the communication service providers (CSPs), the cloud providers, and some enterprises. The CSPs are excited about the potential to leverage increasing network capabilities of their fixed and 5G mobile networks with open cloud environment at the edge of their network to service new enterprise applications. The hyperscale cloud providers such as AWS, Microsoft Azure, Google Cloud, and others are also looking to extend their cloud offerings closer to enterprises who are looking for flexible computing environments on-premise or in the cloud. So, what exactly is edge computing?

Cloud Computing, Closer

Edge computing, or more formally known as Multi-Access Edge Computing (MEC), is a network architecture concept that enables cloud computing, or IT service delivery environment, closer to the edge of a mobile or fixed network. The basic premise of MEC is that by running applications closer to end users or devices, IT services delivered via the cloud can yield much better user experiences. Simply put, MEC is a cloud computing environment at the network edge.



Source: Mobile Experts

Figure 1. Multi-Access Edge Computing (MEC) Concept

So, where is this edge? As illustrated above, today's cloud computing environments exemplified by the very large public cloud providers like Amazon Web Service (AWS), Microsoft Azure, and Google Cloud Platform (GCP), typically have cloud environments or data centers that are some distance away from end users. Most cloud applications are deployed in a handful of locations at most. For instance, AWS, the world's largest public cloud by far, only has 21 Regions and 66 Availability Zones worldwide.[1] In other words, most applications running in the public cloud such as video streaming app like Netflix may actually be handling video stream feeds from hyperscale data centers located hundreds of miles away from the end users' TV screens. While typical video streaming in HD may not require extreme bandwidth or latency requirements, future 8K video streaming to fast-moving vehicles in near real-time may require much higher cloud computing requirements - driving the cloud environment to be much closer to the end users.

With faster networks like 5G that extend the "edge" of the access network closer to the end users, there is a growing acknowledgment by the cloud providers, communication service providers, and enterprises alike that MEC can enable new applications with better user experiences in the cloud computing "as a service" model.

As a subset of cloud computing platform, MEC has three key attributes:

1. MEC provides open application programmable interfaces (APIs) so that third-party applications can access network services or for network management purposes;
2. MEC provides virtualized or software-accessible[2] compute and storage hardware resources; and finally,
3. MEC provides a computing environment to enable value-added services closer to end users.

MEC Classification by Location

The edge clouds can be classified by where MEC is located along with the network "chain" from Core to Access. In this report, we have classified the edge clouds into three different categories, namely: *Near Edge*, *Far Edge*, and *On-Prem*. These categories are based on our expectation of where the communication service providers or enterprises will likely deploy MEC infrastructure in typical network architecture, as shown below.

The physical footprint of an edge cloud decreases as the location of a MEC gets closer to the end user. Moreover, the latency and throughput requirements may drive where a MEC needs to be deployed. For applications that are more generic or largely dependent on signaling requirements are more likely to be candidates for the Near Edge MEC since the low latency, and high-throughput requirements are not the primary drivers. On the other hand, cloud gaming or other applications that demand real-time interactivity may

[1] AWS global infrastructure map: https://aws.amazon.com/about-aws/global-infrastructure/. An Availability Zone is an isolation location within a Region, which can be viewed as a very large data center.
[2] For some situations, a MEC may employ "bare metal" servers instead of running virtual machines on multi-user server hardware

require MEC infrastructure to be closer to the end user at the Far Edge or On-Premise in case of a private 5G enterprise application.

Enterprises	**RAN**	**Metro Ring**	**Core**
10,000's	1,000's	10's - 100's	**No. of Locations (per country/operator)**
Small (1-2 servers)	Medium (4-8 servers)	Large (20-80 servers)	**Physical Footprint**
Highest (less scale)	Higher	Lower (high scale)	**Unit Cost**
Lowest Latency Highest Throughput	Lower Latency Higher Throughput	Low Latency Lower Throughput	**MEC benefits**
On-Prem	**Far Edge**	**Near Edge**	

Source: Mobile Experts

Figure 2. Edge Cloud Definitions

Near Edge

As noted above, Near Edge refers to a MEC infrastructure deployed closer to hyperscale public cloud data centers. Near Edge MEC is typically deployed in the metro area, closer to the Core Network than cell towers. In contrast to Far Edge, Near Edge would handle a higher number of end users or devices and focus on the economies of scale to lower the cost. Moreover, it would typically focus on generic services that do not require ultra-low latency and high throughput requirements. For example, video CDN applications for the consumer market would be a good candidate application that may be sufficient to host at the Near Edge.

Far Edge

Far Edge is the MEC infrastructure that is deployed closer to the end user or devices than the Near Edge. For example, a Far Edge MEC can be deployed near a cell tower or at a C-RAN aggregation site. Since the Far Edge MEC handles less number of users and devices relative to the Near Edge, its footprint in terms of the number of servers, power infrastructure, or physical floor space needed would be lower than the Near Edge.

Typically, Far Edge would run applications that require ultra-low latency and high throughput requirements like cloud gaming, live 8K streaming, etc.

On-Prem

On-Prem edge cloud is similar to the Far Edge, but it specifically refers to MEC infrastructure that is deployed on-premise at enterprise locations. On-Prem edge cloud may be required for certain private 5G enterprise applications that must be on location to meet certain privacy or regulatory requirements.

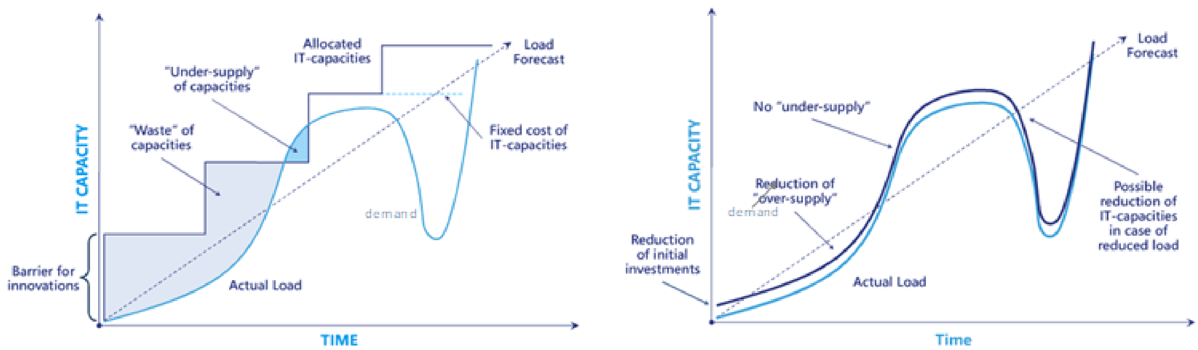
3 WHY EDGE COMPUTING?

Economic drivers of cloud computing and network trends largely explain the rise of edge computing or other terms like "intelligent edge" or "edge cloud" that describe the idea of building compute and storage capabilities at the edge of the network. The idea of resource pooling and re-usage in cloud computing rings true for Telco operators as they transform their network towards "software-driven" networking. This is even more during technology shift to 5G. SDN and NFV transformation from Core to Access Networks provide an opportunity to enable new enterprise opportunities that require lower latency and immense data handling at edges of the network such as immersive video experience at smart stadiums, industrial automation of robots in smart factories, or connected cars in smart cities, for example. Besides the economic benefits that fuel enterprise and Telco adoption of cloud computing, political and regulatory factors are also likely driving distributed cloud architecture or edge computing.

Enterprises Want Hybrid Clouds

With an introduction of cloud computing, enterprises are increasingly shifting IT spending towards "IT consumption via the cloud" model instead of the traditional hardware and software deployment via its own IT staff. The cloud computing paradigms of SaaS such as salesforce.com, zoom.com, etc. and IaaS and PaaS such as AWS, Microsoft Azure, and Google Cloud Platform, are shifting IT spending from CAPEX (i.e., buying hardware and software and deploying on-premise) to OPEX (i.e., rent cloud service) model. From an enterprise perspective, cloud computing is primarily about cost savings. From cloud service provider perspective, it is about pooling and making more efficient use of computing and storage resources.

As depicted in the figure below, cloud computing allows variable costing and the elasticity of adding or removing computing and storage resources unlike the traditional on-premise model which requires initial and subsequent CAPEX based on the demand that is often unpredictable. A key tenet of cloud computing is, of course, for the cloud providers to centralize resources and operation to gain the economies of scale and pass on the savings (with some profit margin, of course) to enterprise customers.



Traditional On-Premise

Cloud Computing

Source: AWS

Figure 3. Cloud computing enables "as a service" model

While public cloud services like AWS, Microsoft Azure, salesforce.com, etc. provide elastic IT scale with a low upfront investment, they entail a certain amount of security risk and loss of control from the enterprise perspective. On the other hand, the traditional on-premise or private cloud, while inherently retaining IT control, requires relatively higher CAPEX investment. Hence, enterprises are keen to adopt a "hybrid cloud" model in which certain "bursty" workloads are run on a public cloud while retaining business-critical workloads on private cloud to retain more control. The enterprise demand for hybrid clouds is driving the distribution of cloud computing facilities with a consistent cloud computing environment.

Telco Network Virtualization in 5G Transition

Cloud computing adoption is not confined to enterprises. Telcos also see the benefits of cloud computing in its network transformation. The network operators have been transforming towards "software-driven" networking for many years, and the NFV and SDN transition that started in core networks is now transitioning to access networks, even more so during the current transition from 4G to 5G. Evolving network densification into virtualized network functions in SDN context provides an opportunity for the Telco operators to transform their distributed networks into distributed edge clouds by strategically adding compute and storage resources.

The distributed edge computing locations can be leveraged to handle Telco workloads like C-RAN and vRAN functions via more cost-effective white-box servers. The Open RAN initiative is an example of this type of paradigm where network functions can run on distributed edge cloud infrastructure. Also, these edge clouds can potentially enable third-party applications that require lower latency. By leveraging edge cloud, new "edge" applications can potentially reduce data transport cost by handling application handling locally instead of transport all traffic to centralized cloud data center hundreds or thousands of miles away.

Political and Regulatory Factors towards Distributed Cloud

While the economic drivers (i.e., cost savings from reduced data transport) and performance drivers (i.e., lower latency) of edge computing are key factors that may drive edge computing, political and regulatory factors are also driving the need for edge computing or more specifically more distributed cloud data centers. National or regional jurisdictions like European GDPR compliance require certain data and processing on that data to reside in certain countries. Even within a single country, local state or municipality may require data to be hosted in data centers within that jurisdiction. While a handful of hyperscale cloud providers dominate the general cloud computing market, regulatory factors will likely require many regional and local cloud locations or providers.

While the economies of scale favor a few hyperscale cloud providers, regulatory factors like privacy and data sovereignty and high-performance local applications like cloud gaming or smart factory applications will likely result in thousands or perhaps tens of thousands of cloud data centers and facilities worldwide.

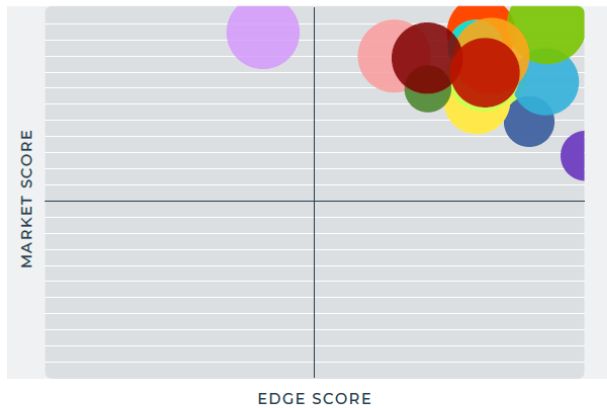
Edge Computing Use Cases

While some of the use cases for edge computing are well established, like content caching and distribution of large files or video streams, many pundits often ask about edge computing use cases. While the technical merits of MEC are certainly plausible, the economics and business models will ultimately determine which edge computing use cases will flourish and warrant capital investments. There have been many works from multiple organizations to identify MEC use cases in the past.

The latest research comes from MobiledgeX, which has identified top 15 MEC use cases ranging from cloud gaming to video delivery. This particular study[3] was based on interviews with experts from technology ecosystem and enterprise verticals to identify 48 edge use cases and assessed against the "market factors" such as market readiness and opportunity size and "edge factors" evaluating the criticality of network performance for those use cases.

[3] MobiledgeX "Edge Navigator": https://www.mobiledgex.com/navigator

	Subdomain	Edge Score	Market Score	Joint Score
1	Multiplayer Gaming	93	95	188
2	Cloud Gaming	83	91	174
3	Manufacturing - Analytics & Mgmt.	80	89	169
4	Hardware - AR/VR	83	86	169
5	GIS Precision Positioning Path Planning	90	79	169
6	V2X Communications	80	86	166
7	Vision / Camera	80	84	164
8	Security - Video Surveillance	75	89	164
9	Unmanned Traffic Management	100	64	164
10	Enterprise	80	80	160
11	Cars - Data & Platform	75	84	159
12	IoT Platform	70	89	159
13	Hardware - Drones	78	80	158
14	Games	88	70	158
15	Video / Media (Downstream)	43	95	138



Source: MobiledgeX

Figure 4. Edge Computing Use Cases from MobiledgeX

Mobile Experts expects many use cases to be highlighted and trialed over the next several years. While it is hard to predict which specific use cases will earnestly drive edge computing, we expect the following use cases to drive the service revenue opportunity from edge computing in the near- to mid-term:

- *Video / CDN* – Video delivery via CDN is a major use case for edge computing historically and will remain a major component of edge computing in the near to mid-term. With video making up the majority of Internet traffic on both fixed and mobile networks today and 4K/8K HD video making up an increasing share of streaming video in the future, CDN will remain a key use case for edge computing for the foreseeable future.

- *Cloud Gaming* – Gaming is already a huge market with an installed base of about 200 million gaming consoles worldwide. Factoring in PC gamers, the potential gaming market is in several hundred million users. While traditional console-based gaming will continue to target high-end gamers, cloud gaming will provide the console-free, multiplayer online gaming experience for a wider market. Google Stadia and upcoming Microsoft xCloud gaming services are early samples of cloud gaming services which will increasingly leverage edge computing to meet high-end gaming experience (i.e., 60-120 frames per second at 4K/8K resolution).

- *Industrial IoT* – Industrial IoT and automation is expected to be a growing segment of a use case for edge computing. With tons of data generated from IoT devices, real-time processing, and analytics at the edge will become a major driver of edge computing.

- *Smart Venues (Entertainment / Retail)* – Large public venues like stadiums and arenas hosting sports and entertainment events will become hyperconnected to high-capacity 5G networks for fan experiences as well as e-commerce/retail applications. 5G, edge computing, and AI will be intertwined at these high-end venues to offer new fan experiences.

- *Automotive (Infotainment / Autonomous Driving)* – Connected car applications such as HD mapping, autonomous driving, and other automotive-related applications will require coordination of high-speed mobile connectivity along with edge computing to facilitate low-latency application requirements.

- *AR / VR* – Consumer and industrial immersive experiences via AR / VR headsets and goggles will drive edge computing in mobile or nomadic context (outside of smart venues) or industrial buildings. Related to the industrial automation applications, AR / VR applications in industrial context can provide productivity gains that will drive some large industrial players to invest in edge computing at their enterprise locations.

- Aerial / Drones – Besides terrestrial automotive applications, new drone applications like autonomous flying that will require real-time access to environmental data will drive some edge computing investments.

For some, such as video content distribution (CDN), edge computing is already providing service revenue for CDN providers that are leveraging MEC cloud technologies such as containers and microservices that are providing real-world efficiencies.

4 Competitive Landscape and Motivations

As a fast-moving new market opportunity, the Multi-access Edge Computing (MEC) landscape is full of old and new players looking to find competitive positions that offer sustained market opportunities. Many of the players are trying to move in before the market firms up towards a de-facto business model and partnership and supplier relationships. In a complex web of companies that make up the "Edge" market as defined in the *stateoftheedge.com* market landscape[4], Mobile Experts view three broad categories of stakeholders that make up the competitive landscape of MEC service providers:

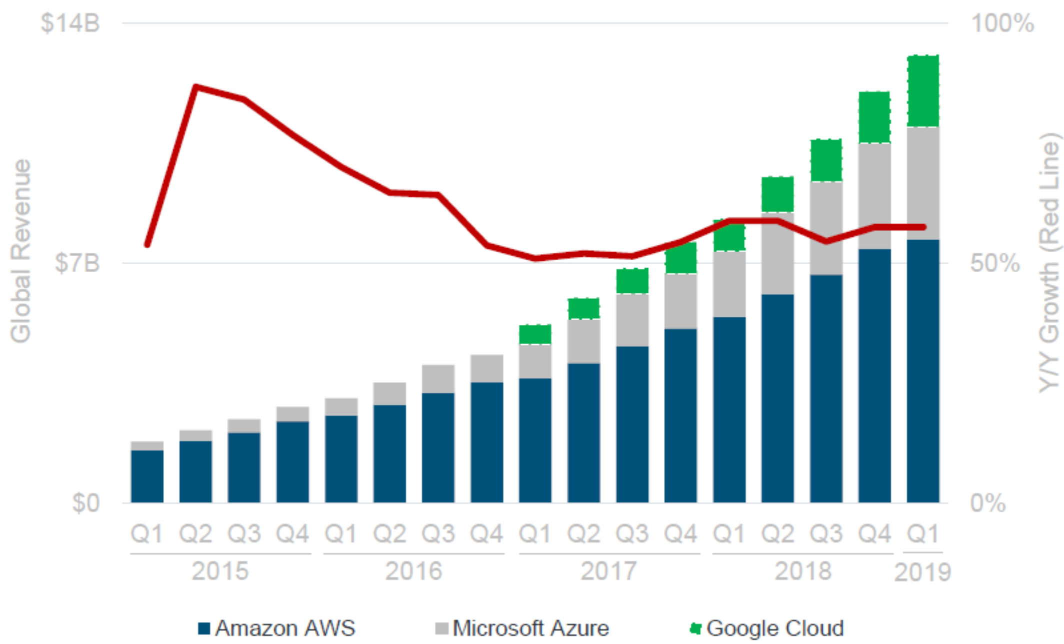
- *Hyperscale Cloud Providers* - looking to extend their cloud computing environment beyond their hyperscale data center facilities closer to end users
- *Telco/Mobile Network Operators* – combine network connectivity with distributed compute/storage resources to provide open cloud infrastructure
- *Neutral Host Providers* – go "up the stack" to provide a cloud computing environment beyond primary real estate offerings in tower and data center facilities

In this section, we primarily explore a competitive landscape of MEC service providers and have not assessed competitive landscape of individual segments of hardware or software suppliers as identified in the "State of the Edge" market landscape in this report.

The Hyperscale Cloud Providers: AWS, Azure, GCP

The cloud computing industry, of which MEC is a subset in our view, is dominated by the hyperscale cloud providers, namely Amazon AWS, Microsoft Azure, and Google Cloud. With AWS pioneering the cloud computing industry over a decade ago, the public cloud infrastructure market now stands at almost $50B industry and continues to grow quickly with a 40-50% yearly growth in recent years.

[4] https://www.stateoftheedge.com/projects/landscape/



Source: Mary Meeker, Internet Trends 2019

Figure 5. Hyperscale cloud providers lead the cloud computing infrastructure market

The key proposition of these very large cloud providers is providing inexpensive cloud compute resources on-demand, and the cloud providers can provide inexpensive computing environment through hyper-scaled data center operations throughout the world. To derive the economies of scale advantages that they enjoy, these cloud providers build a select number of huge data centers based on inexpensive land that is close to power generation sites to tap into inexpensive power which is a major cost component of these hyperscale data centers. For example, AWS, which is the world's large public cloud only has 21 regions with 66 availability zones. In other words, each data center that AWS builds, for example, each of 3 or more data centers in a region, is big. For example, a key AWS architect has noted that AWS typically build a data center capacity to about 30MW – equivalent to 50,000-80,000 servers. Compared this to 20-80 servers for a Near Edge MEC data center, the hyperscale cloud providers build massive data centers – 1000- 2000x times bigger!

Although their advantages come from building these massive data centers to offer "cheap" cloud computing environment for developers and enterprises, there is a growing desire for them to offer cloud infrastructure services closer to end users for myriad reasons such as data security, regulatory compliance, etc. For demanding customers, there is a growing acknowledgment by the cloud providers that they need to provide hundreds and maybe even thousands of regions to satisfy a growing list of reasons including regulatory compliance, latency performance, and fail-safe redundancy.

And, the major cloud providers are working to distribute their cloud computing environment deeper into networks today for two key drivers: IoT and hybrid cloud. To handle tons of data expected from IoT devices, the major cloud providers have IoT-specific cloud services that focus on secure access to IoT devices under intermittent connectivity scenarios. For hybrid cloud support, the cloud providers offer public cloud services that can run on enterprise data centers.

Amazon Web Services

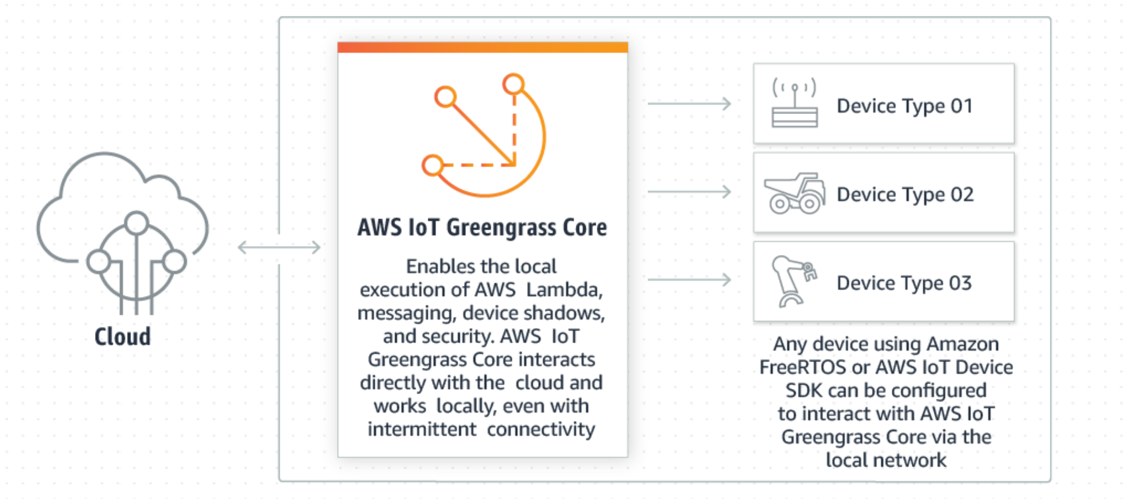
As noted previously and shown below, AWS is characterized by very large data centers globally distributed across multiple regions. As of the writing of this report, AWS has 21 regions with 66 availability zones with several more coming online in the near future. To extend the AWS cloud computing environment deeper into enterprises and closer to end points, AWS has two cloud services to address this: *AWS Greengrass* and *AWS Outposts*.

Source: Amazon AWS

Figure 6. AWS Global Infrastructure Map

AWS Greengrass is a cloud service specifically designed to solve intermittent connectivity issue surround IoT applications. It is essentially a software that extends AWS cloud capabilities to IoT devices by providing SDKs for 130+ supported devices[5] and providing API calls to the AWS cloud. As shown in the figure below, a basic architecture is for supported IoT devices to use supported SDK from AWS to securely access AWS cloud.

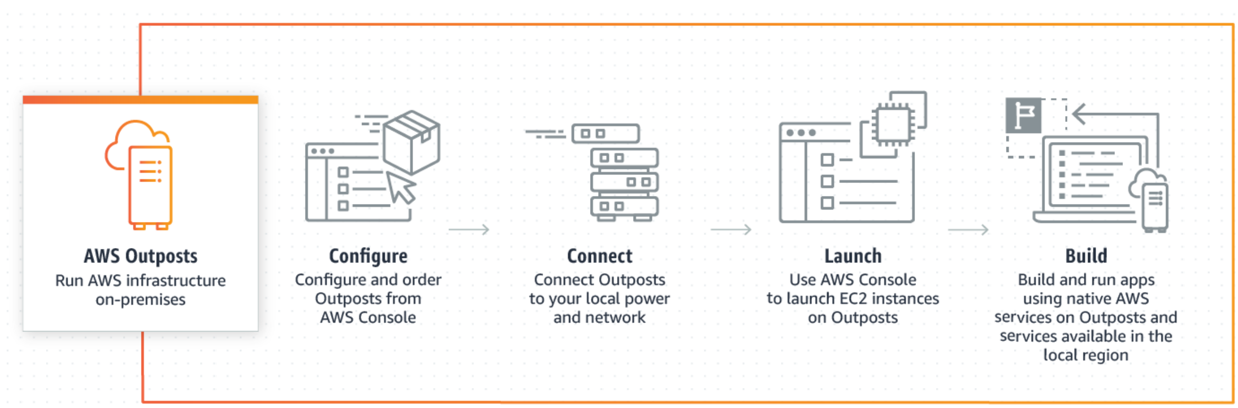
[5] AWS Greengrass supported IoT devices: https://devices.amazonaws.com/search?page=1&sv=gg



Source: Amazon AWS

Figure 7. AWS Greengrass Architecture

Launched in November 2018, AWS Outposts addresses the increasing enterprise preference for hybrid cloud operation-- certain workloads are run in the public cloud while other business-critical or compliance-related workloads are run on on-premise hardware. AWS Outposts essentially provides the same server hardware found in AWS cloud infrastructure with either the VMware Cloud on top or with native AWS API so that enterprises can run AWS cloud services on-premise.



Source: Amazon AWS

Figure 8. AWS Outposts Overview

Microsoft Azure

According to Microsoft, its Azure global footprint encompasses more than 100 data center facilities covering over 50 regions worldwide.[6] With its deep enterprise relationships and transition to cloud services (e.g., Office 365, Azure, etc.), it is not surprising to see a "deeper" cloud infrastructure presence than others.

Source: Microsoft

Figure 9. Microsoft Azure Global Infrastructure Map

Microsoft saw the enterprise adoption towards hybrid cloud computing early on. Back in mid-2017, Microsoft launched *Azure Stack,* which is similar to the AWS Outposts solution. With its long history of working with computing OEM vendors like Lenovo, Dell, and HP, Microsoft Azure Stack essentially offers public Azure as a platform inside an enterprise's own data center. Instead of working with one specific hardware configuration like in AWS Outposts, the Azure Stack allows the enterprises to choose from multiple server vendors. Similar to AWS Greengrass, the *Azure IoT Edge* is Microsoft's IoT edge computing offering.

Google Cloud

According to Google, the Google Cloud Platform (GCP) is available in 61 availability zones across 20 regions worldwide. Interestingly, it also highlights 134 "network edge locations" with 2-3 edge locations in each of major metro markets in North America and

[6] https://azure.microsoft.com/en-us/global-infrastructure/regions/

up to 8 edge locations in some major metro markets in Europe and APAC. In some metro markets, two or three edge locations is common.

Source: Google

Figure 10.   Google Cloud Global Infrastructure Map

While somewhat behind the other two major cloud providers, Google has similar edge computing offerings as AWS and Microsoft. Google's *GKE On-Prem* is Google's answer to AWS Outposts and Microsoft Azure Stack in allowing enterprises to run public cloud services in enterprise data centers. GKE, which stands for Google Kubernetes Engine, manages containers in the Google Cloud, and the GKE On-Prem essentially brings this service to enterprise data centers.

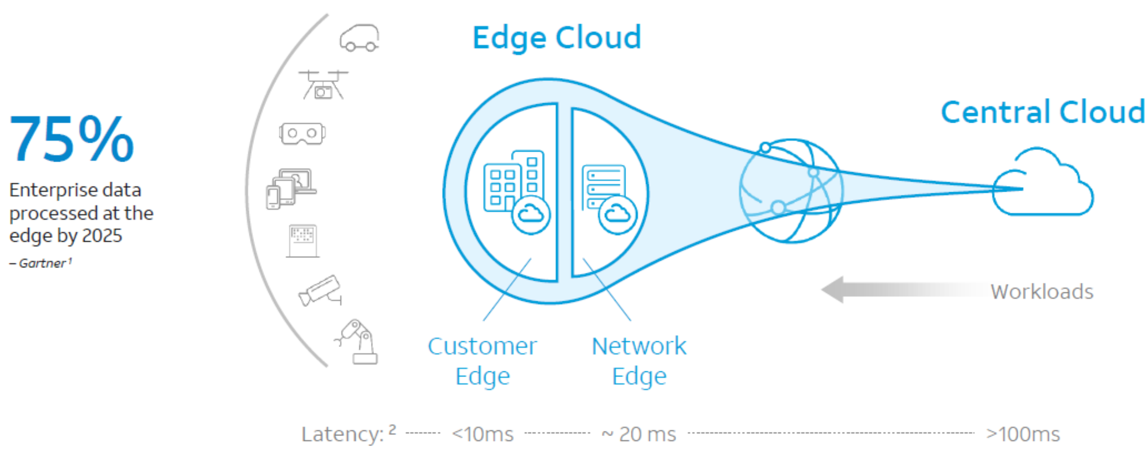
It is clear from the latest cloud service offerings from the three major cloud providers that they see immediate edge computing opportunities in IoT and enterprise hybrid cloud adoption. AWS has a lead in the IoT area with hundreds of IoT devices that it supports through its AWS Greengrass offering. Meanwhile, Microsoft has a lead in the hybrid cloud space with its Azure Stack offering. Google is a bit behind the other two, but the pace of innovation for these hyperscale cloud providers is well documented. For new MEC services like cloud gaming, autonomous driving, etc., the jury is still out.

Telecom Operators

Most major network operators have edge computing initiatives in trials or limited commercial deployment. For some, edge computing is an extension of their NFVI network transformation that started in Core networks out to the edge of their network. Coinciding with 5G network deployments, the network operators are exploring various edge compute business cases around private LTE/5G applications for smart factories, healthcare, the venue hosted events, and cloud gaming, to name a few. At this early stage, the operators' activities span across multiple vectors, including open source projects, standards, trials, and partnership developments with the cloud providers and large enterprises. One notable operator project related to edge computing is Rakuten's vRAN deployment in which it is expanding edge compute facilities across tens of Near Edge data centers and thousands of Far Edge facilities for both vRAN and future MEC applications.

AT&T

AT&T Business group sees the benefits of edge computing in terms of reduced latency and efficiency gain in data handling at the Network and Customer Edge. It is actively promoting these benefits in the context of its fixed and 5G mobile networks.



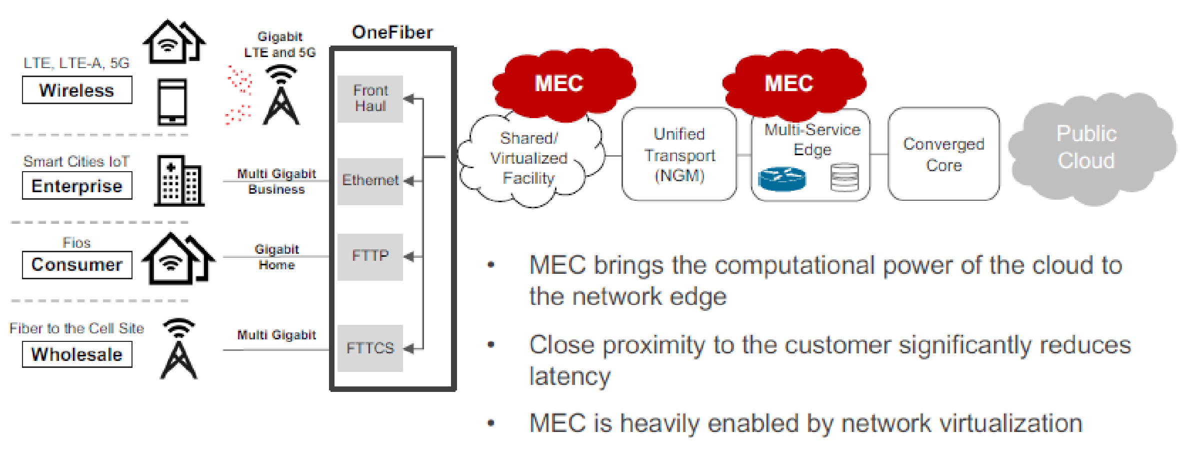
Source: AT&T presentation at Big 5G Event, 2019

Figure 11. AT&T Network Edge Compute provides latency and efficiency gains

AT&T edge computing strategy appears to be centered around a partnership with the public cloud providers and server OEMs. For example, AT&T Business group has partnered with Microsoft Azure under its "network edge compute" (NEC) model in which traffic running on AT&T network layer is transported to Microsoft Azure public cloud. Also, AT&T announced a partnership with HPE to promote HPE's Edgeline servers with AT&T's MEC services. AT&T Business is publicly promoting its MEC services for the following key verticals, including the stadium, healthcare, manufacturing, and retail. Concerning its MEC strategy and target verticals, the company has announced MEC trials with Rush University Medical Center (healthcare), AT&T Stadium in Dallas (venue events), and Samsung semiconductor plant in Austin (manufacturing). Also, the company is working with several startups at its Foundry Labs to trial various MEC use cases, including drone operations.

Verizon

Along with fiber, spectrum, SDN, Verizon views MEC as one of the critical technologies for 5G. Not only does it provide a better customer experience through cloud computing services at the network edge, but it can also enable new market opportunities along with 5G. Verizon has publicly announced its first MEC launch in the fourth quarter of 2019 and expects that it will enable new business revenue models.



Source: Verizon Investor Presentation, Feb 2019

Figure 12. MEC is a key enabler of network convergence and 5G services for Verizon

Whether the new MEC business revenue opportunity involves fixed wireless access or some other application is unknown at this time, but based on its announcement around MEC trials, the location of its initial MEC launch may be in Houston.

Verizon has identified the following use cases for edge computing:

- Immersive virtual reality applications
- Self-driving cars
- Remote-controlled robotics
- Industrial automation
- Venue hosted events
- Retail
- (Cloud) gaming
- Video analytics

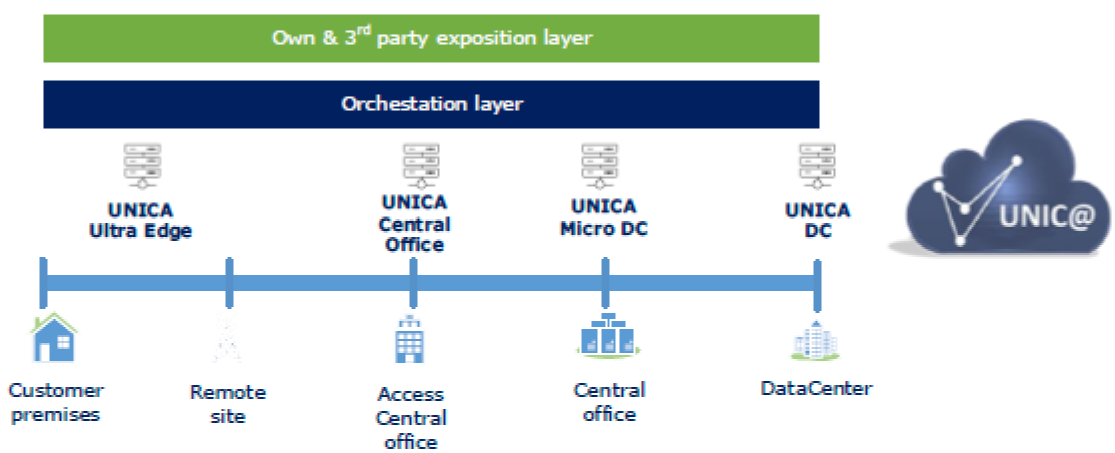
Deutsche Telekom

Deutsche Telekom views 5G and MEC as key enablers of extending 5G services into campus networks. For example, smart factory applications such robotics need private 5G campus along with edge cloud infrastructure to help large industrial enterprises with their digital transformation. In this effort, Deutsche Telekom has spun-out edge compute business unit, MobiledgeX, as a standalone company to help bridge the telco cloud with application/developer-friendly cloud providers such as AWS, Microsoft Azure, and Google Cloud.

The network operator has six edge compute sites with MobiledgeX platform and may have several MEC sites in low teens by the end of 2019. While there may be an opportunity for hundreds of MEC data center sites, it depends on how quickly private 5G networks would be adopted by large enterprises.

Telefonica

Telefonica is basing its MEC program based on its UNICA program which started its network virtualization initiatives many years back. As its network virtualization extends from Core to Access networks, it has started its UNICA EDGE program which aims to identify MEC locations where fixed and mobile services can be converged.



Source: Telefonica Open Access and Edge Computing Whitepaper, 2019

Figure 13. Telefonica MEC based on UNICA NFV infrastructure

China Mobile

Like other major operators, China Mobile is currently focused on 5G network buildout. Meanwhile, it is conducting several testbed trials as listed below to further evaluate edge computing implications on its network and business opportunity. Related to this effort, the operator has embarked on its "Pioneer 300" initiative whereby it will evaluate 100 edge computing ready locations; identify 100 "edge capability" APIs; and, develop 100 partnerships in edge computing.

Number	Name	Area	Cooperation
1	Smart City Video Networking Service Platform Based on Mobile Edge Computing	Smart City	Inspur
2	Smart City Video Networking Service Platform Based on Mobile Edge Computing	Smart City	Tridium
3	Seven-layer full-scale Experimental Intelligent Construction Pilot Based on Edge Computing Service Architecture	Smart City	China Construction Group
4	Application of Edge Intelligence in Smart City	Smart City	Alibaba
5	Digital Production Line Based on TSN and vPLC	Intelligent Manufacturing	Huawei
6	Industrial Flexible Manufacturing Based on Wise-PaaS	Intelligent Manufacturing	Advantech
7	Smart Factory Testbed	Intelligent Manufacturing	Ericsson
8	Smart Test Eye: An Automatic Detection Scheme for Intelligent Manufacturing	Intelligent Manufacturing	Lenovo
9	Industrial Vision Application Based on OpenIL	Intelligent Manufacturing	NXP
10	New Network of Industrial Internet Testbed (opcua&tsn)	Intelligent Manufacturing	CertusNet
11	Application of Edge Computing in CDN	Live and Games	Tencent
12	5G Fast Game Based on Edge Computing	Live and Games	China Mobile
13	MEC Based 8K 360° VR Video Broadcasting	Live and Games	Intel
14	12K VR Panoramic Video On Demand based on Edge Cloud	Live and Games	China Mobile
15	Application of Edge Computing in Vehicle Interconnection	Vehicle Interconnection	Baidu

Source: China Mobile Edge Computing Technical Whitepaper, 2018

Figure 14. China Mobile Edge Computing Open Lab Testbed Projects

Korea Telecom

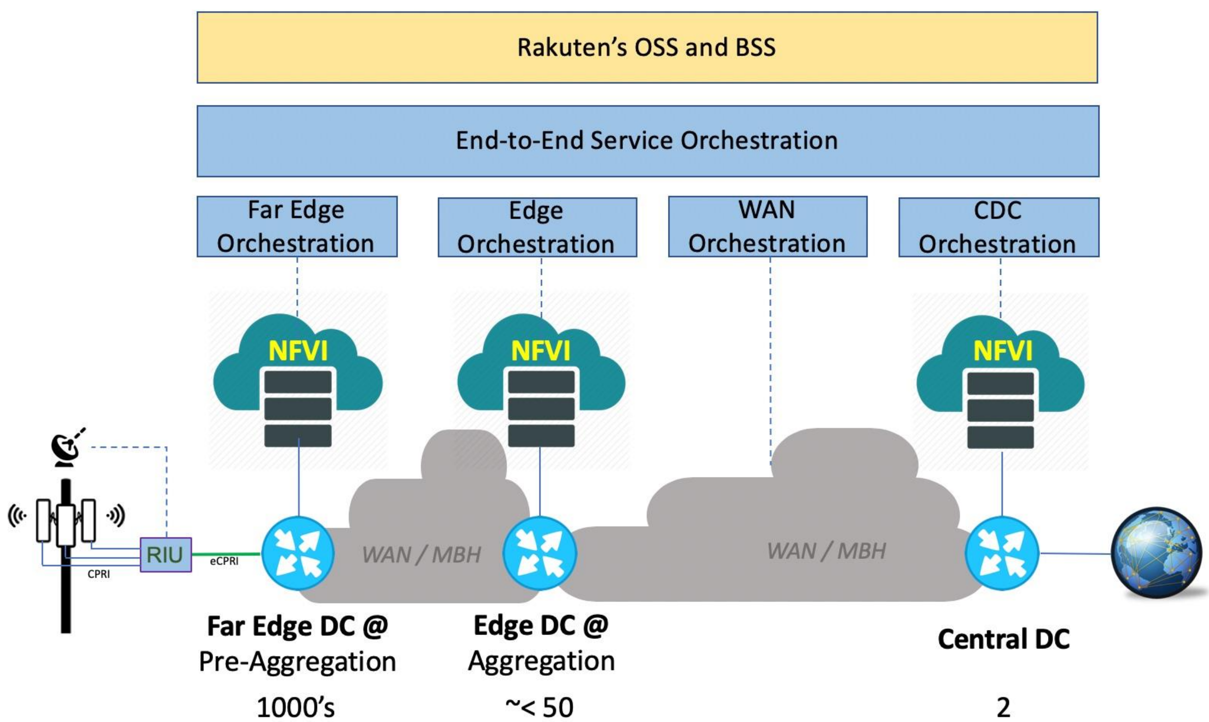
Korea Telecom (KT) has been one of the leading operators in 5G and edge computing deployment. Coinciding with its 5G network and service launch, the operator has built edge computing environment in 8 central offices nationwide. In the edge cloud locations, certain 5G Core User Plane (UP) and RAN Central Unit (CU) functions are located. In addition, MEC servers perform data processing for 5G devices in the vicinity of the edge sites. KT has announced its plans to use MEC centers for deployment of new 5G services for autonomous cars, smart factory, AR and VR services.

NTT Docomo

NTT has been operating its private cloud since 2015. Its private cloud called Docomo Cloud Platform (DCP) now has 200k cores of compute capacity across 11 regions as of 2018. As it builds out a 5G network, the DCP is expected to expand into more distributed sites and leverage container technologies like Akraino to extend Kubernetes onto its OpenStack based DCP.

Rakuten

Rakuten's mobile network buildout is a major project undertaking that leverages network function virtualization and pushes the edge computing concept further to enable core network functions and enable a network foundation for future MEC services. With heavy computing resources required, the scope of server deployments at the Near Edge and Far Edge data center facilities are likely much higher than typical MEC facilities that do not have to take on the core network functions. In the near term, Rakuten's vRAN network buildout is expected to heavily influence the edge compute expenditure as the core network buildout will drive edge compute server deployments at the Near Edge and Far Edge data centers.

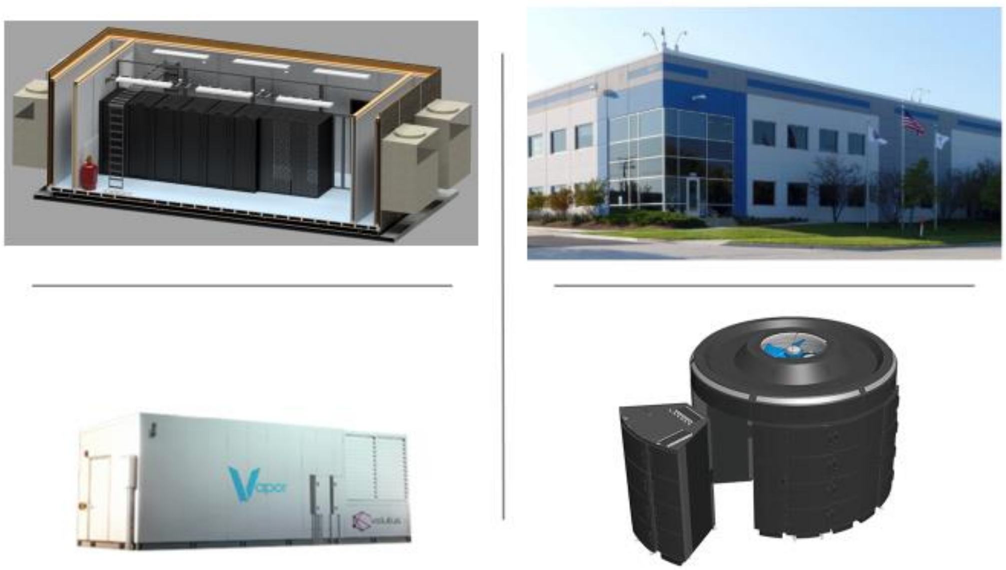


Source: Cisco

Figure 15. Rakuten Cloud Platform Overview

Neutral Host Providers

In addition to the network operators and the major cloud providers, some tower and data center infrastructure providers, whose business models are founded on multi-tenancy and neutral hosting, are also exploring edge computing opportunities as operators look to overlay some compute resources as they densify their network. Some new infrastructure providers like Vapor IO, EdgeMicro, and others are looking to deploy both traditional data center warehouses as well as self-contained chambers with racks of servers to provide "right" amount of server capacity to meet the expected demand (see figure below).



Source: Vapor IO, EdgeConneX, EdgeMicro

Figure 16. Samples of "Edge" Data Center Facilities

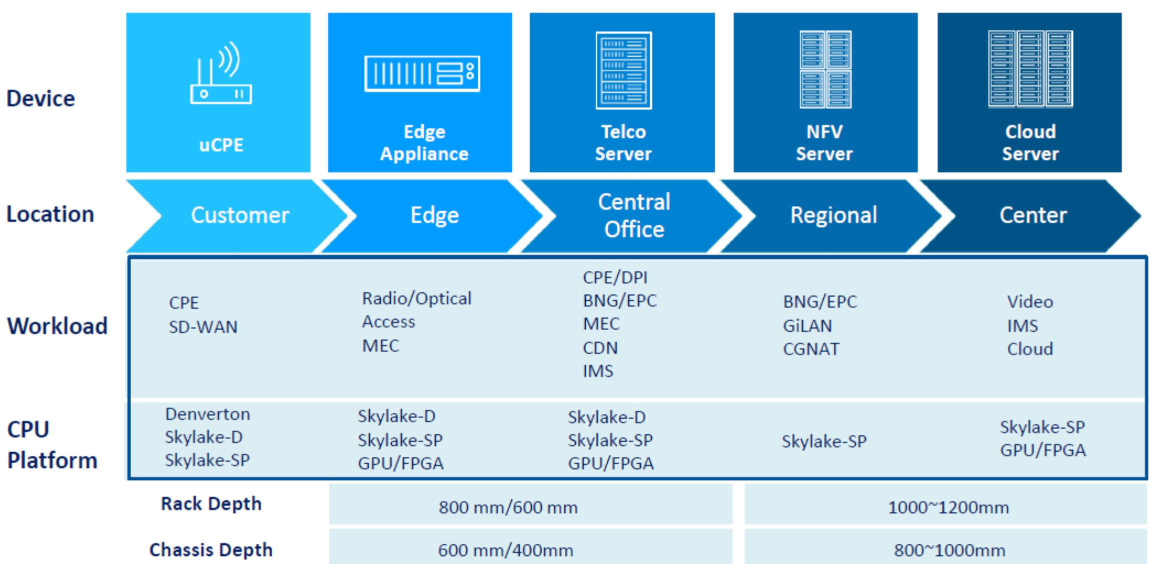
While hyperscale providers typically deploy 30 MW+ data center facilities in some of their regions, the edge-focused neutral providers are looking to deploy much smaller "micro" data centers with 10's-100's kW of capacity to target network operators, the hyperscale cloud providers and enterprises looking for "edge" locations that can satisfy low-latency performance or location compliance requirements.

5 TECHNOLOGY INITIATIVES

Edge computing is a convergence point for IT and Telco technology trends. With the major cloud providers driving innovation on both hardware and software fronts, the edge computing ecosystem can largely leverage those innovations for hardware servers and switches. The challenges largely remain in MEC implementation of edge infrastructure with the latest cloud computing technologies of cloud-native microservices and containers to run dynamically orchestrated computing and networking functions at the edges of the network while maintaining end-to-end service orchestration across carrier and enterprise networks.

Server Hardware

Server hardware designs depend on multiple factors, such as performance requirements based on workloads, environmental considerations like physical and cooling constraints, etc. While server hardware designs are heavily influenced by the requirements from the major cloud providers since they purchase millions of units for their hyperscale data centers, edge computing server design brings different requirements. Depending on where the "edge" is, the edge server hardware can look quite different. For Near Edge data center deployments, the edge server would most likely be a rack or blade server. For Far Edge deployment near a cell tower, it could be a compact design housed in NEBS or IP-65 certified enclosure for harsher environments.



Source: QCT

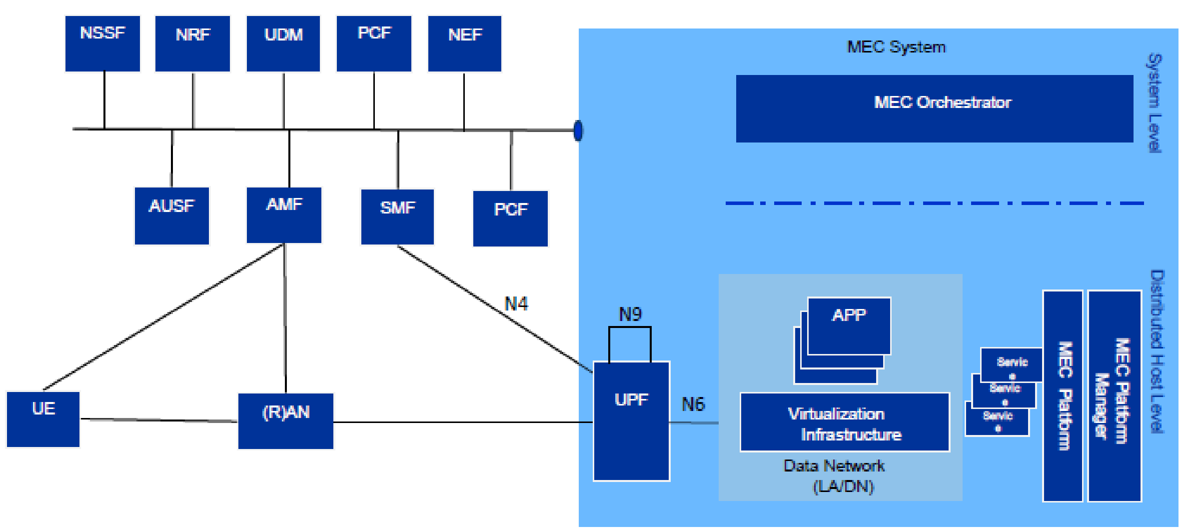
Figure 17. Different edge servers are available depending on location/workload

In addition to different physical designs, the edge server hardware can have different processor implementations based on different workloads. For heavy call processing functions involved in Telco-centric applications like vRAN, high-performance CPU processors with a high count of cores may be needed vs. heavy parallel processing workloads like video may require more GPU processing cores. In some cases, FPGA hardware acceleration may be required to handle some specific workloads like LDPC coding for error correction, for example. The diversity of workloads and types of edge servers will bring unique design requirements.

MEC Software Stack

The hardware components that makeup MEC infrastructure at the edge are only one piece of the puzzle. A software stack is the heart of a MEC server that brings hardware, applications, and network and public cloud services together to enable accelerated processing at the edge while providing seamless management and orchestration of end to end services across the public cloud, at the network edge, and on-premise locations. While there are many interpretations or definitions of what constitutes a "MEC software stack," there are some basic components that make up the stack:

- Virtualization infrastructure
- MEC and NFV orchestration
- MEC applications
- MEC platform



Source: ETSI MEC

Figure 18. MEC Framework in 5G Network Context

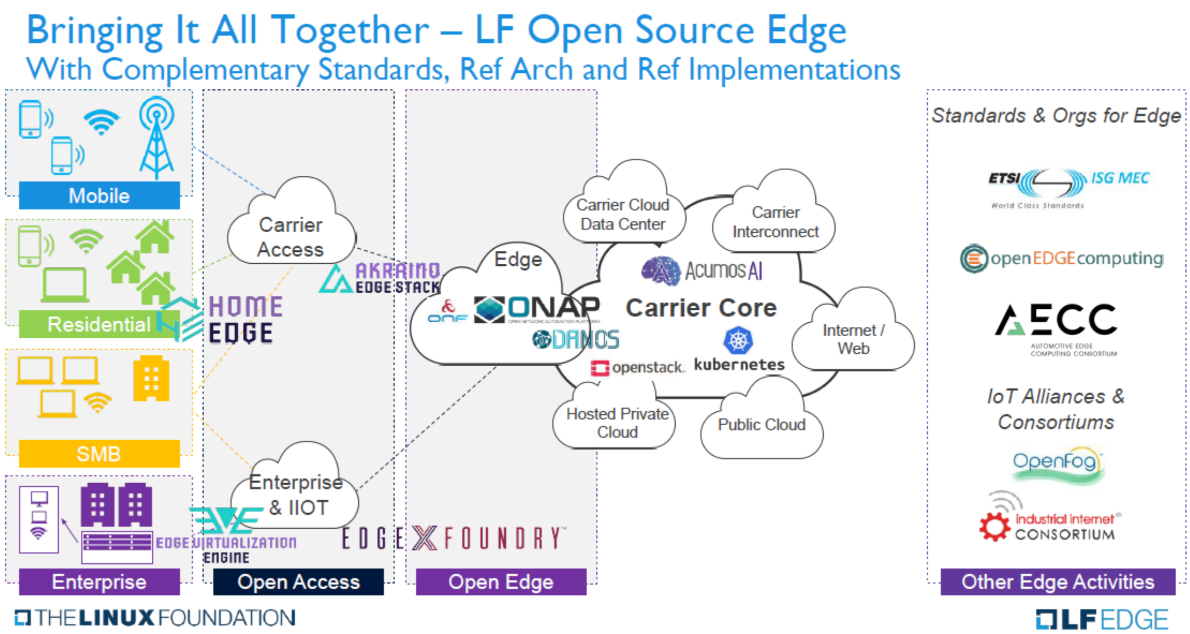
The above diagram (from ETSI MEC) highlights some of these components in the context of 5G Core as defined by 3GPP. Here, a MEC host (in the blue box) is depicted as an

Application Function (AF) in 5G Core so that traffic can be forwarded onto a 5G Core or sent to right MEC host servers for local-breakout or send onto the 5G Core. Besides the MEC interaction with 5G Core and RAN (or fixed network), the MEC host contains: 1) virtualized infrastructure of compute, storage, and networking resources; 2) MEC platform to provide and consume MEC services; and, 3) MEC applications instantiated on the virtualization infrastructure. The NFV orchestration of underlying MEC server hardware is handled at the host level while the system level MEC orchestration handles end-to-end service orchestration and assurance.

Standards and Open Source Projects

A key challenge in edge computing is properly implementing MEC. While the hardware challenges are somewhat self-contained in the sense that a hardware server can be implemented that meet certain physical, power, performance constraints of individual units, the software challenges are many. Containerized microservices, while providing great flexibility in distribution and execution across different environments, bring huge challenges of properly orchestrating with other software functions – e.g., working with 5G Core, RAN, enterprise applications, management systems, etc. While standards provide frameworks and reference architectures, the implementation and system integration can often reveal incompatibilities.

While ETSI MEC group has been working on edge computing definitions and standards for many years, we have seen a growing number of commercial and standards organizations providing different interpretations of what edge computing is and how it should be implemented under different use cases. Today, there are many different definitions and open source implementations of edge computing. While the standards and open source projects are fragmented at the moment, the "code-first" open-source bodies are consolidating around some initial use case implementations. Also, there is a growing collaboration among some of these standards and open source projects, with the aid of some key operators and leading vendors.



Source: Linux Foundation

Figure 19. Context Diagram of LF Edge and Standards

While the diagram above shows one snapshot of various standards and organizations actively looking to push edge computing, below are some key organizations and open source projects that are driving the industry at the moment. Of course, commercial success will still depend on equitable business models and companies looking to apply edge computing to solve specific industry problems.

3GPP

While 3GPP is often referenced in the context of RAN standards that drive the mobile industry, its *SA2 Architecture* group defines standards for disaggregated mobile Core architectures including control and user plane separation (CUPS) and URLLC which are key architectural paradigms that facilitate edge computing.

Akraino

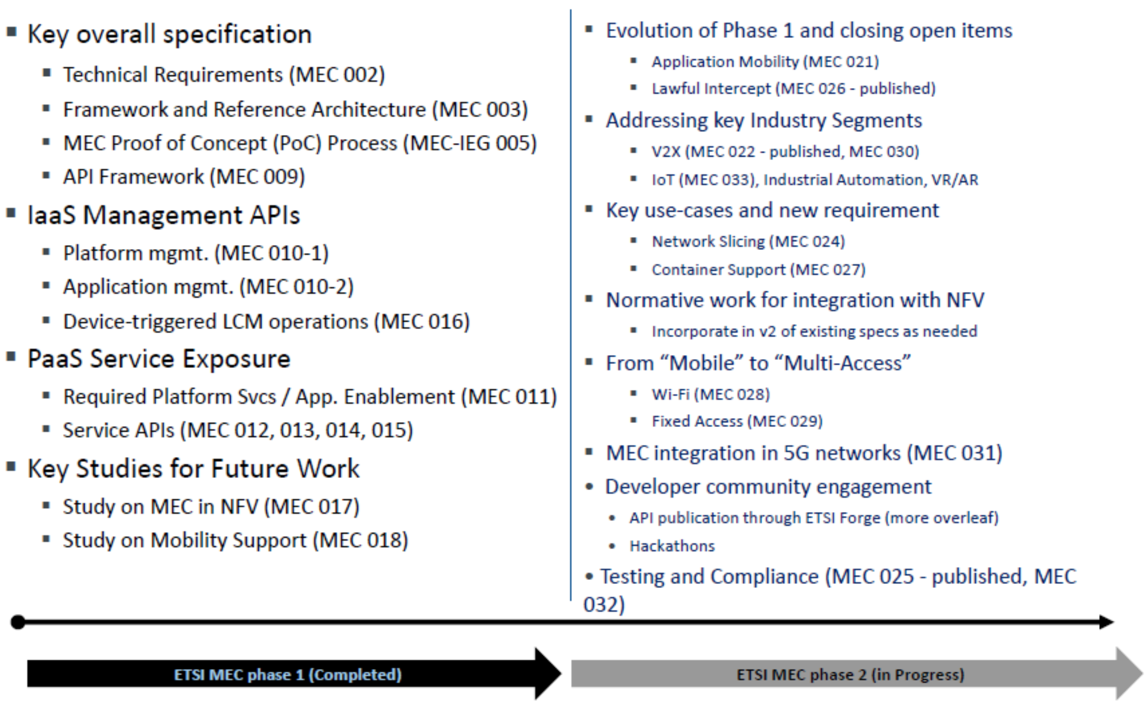
Akraino Edge Stack aims to create an open-source software stack that supports cloud services optimized for edge computing. The Akraino Edge Stack is designed to improve the state of edge cloud infrastructure for enterprise edge, OTT edge, and carrier edge networks. The Akraino release 1.0 was published with 10 "blueprint" use cases ranging from industrial IoT, 5G, uCPE, edge media processing, etc.

Cloud Native Computing Foundation (CNCF)

The Cloud Native Computing Foundation (CNCF) is an open-source software foundation working to promote cloud-native computing so that companies can run scalable applications in the public, private, and hybrid clouds. Specifically, the organization promotes the use of containers, microservices, immutable infrastructure, and APIs. As a part of the Linux Foundation, the CNCF hosts open-source projects including Kubernetes, Prometheus, Envoy, and many others. The foundation has close to 200 members and provides a certification program to ensure stable APIs and identify "production-ready" certified Kubernetes.

ETSI Multi-access Edge Computing (MEC)

ETSI MEC working group is defining standards for multi-access edge computing (MEC) rather than an open-source project. It is working on reference architecture and API specification with a focus towards Telco cloud applications. ETSI MEC is actively pursuing three deployment trials based on key use cases including CDN at the edge, MEC in smart factory networks, and VR cloud gaming over a 5G network. This standard body is working to help define the application enablement framework and service-related and management and orchestration APIs.



Source: ETSI MEC

Figure 20. ETSI MEC is working on 5G integration and key use cases

As delineated above, ETSI is now in phase 2 of its lifecycle after establishing key frameworks in phase 1. In phase 2, it is working towards more "development focused" initiatives, engaging developer community, and helped to define more details of how MEC will integrate into 5G networks and some specific use cases.

Linux Foundation (LF) Edge

LF Edge is a new umbrella project that encompasses several open-source projects, including:

- *Akraino* - for Edge Computing stack;
- *EdgeX Foundry* - IoT framework;
- *Open Glossary of Edge Computing* – a collection of terms;
- *EVE* - virtualization engine; and,
- *Home Edge* - residential edge computing case from Samsung.

According to the LF Edge homepage, the Foundation wanted to consolidate all edge computing-related projects under an umbrella organization to provide a "neutral structure for building a diverse open source community." LF Edge appears to be the latest trend at the Linux Foundation which has a growing number of open-source projects. By combining, the projects can presumably leverage common infrastructure and resources for faster development and innovation.

Open Network Automation Platform (ONAP)

ONAP within the Linux Foundation provides an open architecture and implementation of policy-driven orchestration and automation of physical and virtual network functions. It is essentially creating a management platform for physical and virtual network elements. It is defining Management and Network Orchestration (MANO).

Open Platform for NFV (OPNFV)

OPNFV is an open-source project within the Linux Foundation that helps define a common open source NFV platform. OPNFV works closely with ETSI to promote consistent open NFV standard. OPNFV continuously release versions that have been integrated, tested, and are deployment-ready. Along with its "sister" project, OpenDaylight, which provides the SDN-based control for OPNFV, OPNFV promotes an open platform for network virtualization.

Telecom Infra Project (TIP)

TIP Open Compute and Edge Computing project groups focus on lab and field implementation for server hardware and edge computing services at the edge. For the Edge Computing project group leverages open architectures, libraries, and software stack to create MEC implementation. The project focuses on 5G and IoT service deployments and will explore different business model implementations.

6 EDGE COMPUTING BUSINESS MODELS

The Multi-Access Edge Computing (MEC) is a networking architecture that essentially distributes cloud computing to the edges of fixed and mobile networks. Hence, it is reasonable to expect telcos and mobile operators to play a key role in MEC business models with points of presence in their distributed networks. In the early stages of MEC market development, it is unclear which business model will come on top. Here, we explore several business models that the Telcos, the hyperscale cloud providers (e.g., AWS, Microsoft Azure, Google), and neutral host providers can enable for the enterprise customers.

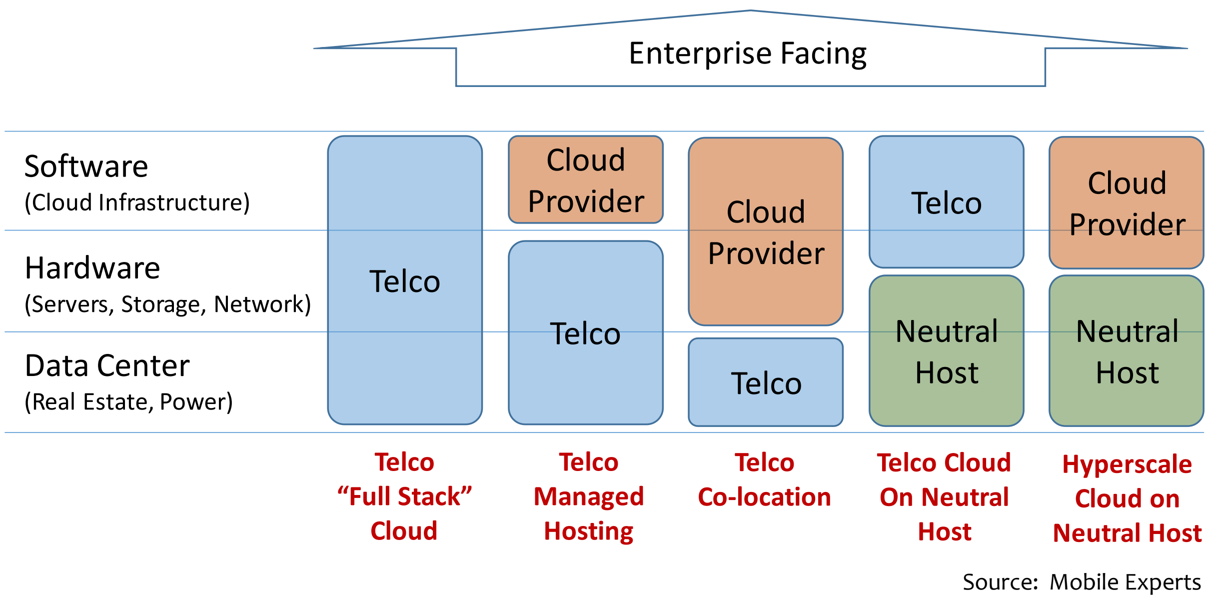


Figure 21. Edge Computing Business Models

While the new MEC architecture can stimulate many different business models, Mobile Experts has identified five business models related to MEC services towards enterprises. These business models are based on key assets and capabilities that major stakeholders enable in creating a distributed cloud computing environment that enterprises or third-party application developers can leverage to create new MEC applications. They are:

1. Telco "Full Stack" Cloud
2. Telco Managed Hosting
3. Telco Co-location
4. Telco Cloud on Neutral Host
5. Hyperscale Cloud on Neutral Host

Telco "Full Stack" Cloud

As the name implies, in this business model, a telco or mobile operator builds a full-stack edge computing environment for enterprise customers. Here, a mobile operator, for example, would build out the cloud computing environment across its network footprint for enterprises to provision and scale enterprise-developed or purchased MEC application software on top of the operator's distributed cloud infrastructure. In this model, the operator would be responsible for investing in necessary hardware including servers, storage, and networking, as well as AWS-like cloud computing software infrastructure environment such that enterprises can provision and scale MEC services on-demand.

In this model, a telco or mobile operator takes on the investment burden for all aspects of cloud computing infrastructure including physical data center facility, hardware including servers, storage, and networking, and MEC software for edge computing inside. And, enterprises would consume these physical resources on an OPEX basis. Besides leveraging "natural" assets of physical spaces and distributed networks, telcos or mobile operators need to build up cloud computing capabilities like those of AWS, Microsoft Azure, and Google GCP and further hone developer relationships and ecosystems to easily provision and scale third-party applications on the telco's distributed cloud infrastructure.

This business model demands most out of telcos and would extend telcos' core competency beyond network connectivity into data center and cloud computing capabilities. Based on historical trends of telco's moving away from pure data center businesses (e.g., Verizon divestiture of Terremark), Mobile Experts believes that this particular business model would less likely be pursued.

Telco Managed Hosting

In the "Telco managed hosting" business model, a telco or mobile operator would own and manage the physical infrastructure assets, including the physical facility and associated power systems as well as hardware equipment including servers, storage, and networking. On top of these physical cloud infrastructure assets, the cloud providers would deploy their cloud infrastructure software and manage the relationships with enterprises and developers. Here, telcos would essentially be suppliers of distributed cloud infrastructure to the cloud providers who would manage the customer relationships with enterprises and developers.

A hybrid version of this model is where the telco would provide MEC "brokering" service to multiple hyperscale cloud providers through software development kits (SDKs) that provides application run-time environment that exposes the telco or mobile operator's network services to a specific cloud provider's IaaS or PaaS environment. Examples of these include Ericsson's Edge Gravity and MobiledgeX that essentially act as "middlemen" between telco/mobile operator's distributed cloud infrastructure to the hyperscale cloud infrastructures of the major cloud providers like AWS and Microsoft Azure.

Telco Co-location

The "Telco Co-location" business model is probably the simplest form of MEC business model for telcos since it only involves the telcos or mobile operators to offer their distributed points of presence along with their networks to the hyperscale cloud providers to use in their MEC cloud infrastructure deployments. This is a form of simple data center co-location business whereby the physical facility space along with necessary WAN network connectivity and power infrastructure is supplied by the telco operators, and the cloud providers would own and manage both hardware and software components that make up the MEC cloud infrastructure. Since this business model requires less burden and operational complexity, it would naturally be a lower-margin business for telcos since they would essentially become data center providers like Equinix and Digital Realty in this arrangement. In our survey, key operators expressed a preference to take a more active role than this business model allows.

Telco Cloud on Neutral Host

The three previous business models explored assumes that a telco or mobile operator has the ideal physical facility for MEC data centers since their distributed network presence would provide an opportunity to house MEC cloud infrastructure equipment. A key assumption here is that Central Offices (CO) that dot incumbent telco networks would be ideal locations for MEC data center facilities. Open Networking Lab's Central Office Re-architected as a Data Center (CORD) project is a key example of this initiative to convert old CO's into modern-ay data center facilities at the edge of operator networks.

Of course, the reality of converting old facilities into new cloud computing-friendly environment is not straightforward. A simple fact is that a CO is not a data center. CO's were designed in the days of old dial-up PSTN networks with different requirements. A typical CO has constraints around how much power can be dissipated per rack cabinet and rack equipment depths are typically shorter than typical data centers. These limitations may require CFOs at telco/mobile operator to assess whether the retrofit cost is necessary or desirable. Under this backdrop, we expect some MEC locations will be provided by neutral host providers who can provide better economics for telco or cloud providers – assuming that multiple tenants can be hosted at particular locations.

In this business model, Telco would offer "upper" layer MEC components on top of underlying physical space, hardware, and possibly some lower-layer cloud computing infrastructure. For example, Vapor IO's circular chamber of server racks can be the basis for a Telco-provided MEC environment that telcos would offer up to enterprises.

Depending on the economics of neutral host provided MEC infrastructure, certain telcos or mobile operators may choose this path as this may offer faster time-to-market and lessen the operational complexity and market risks.

Hyperscale Cloud on Neutral Host

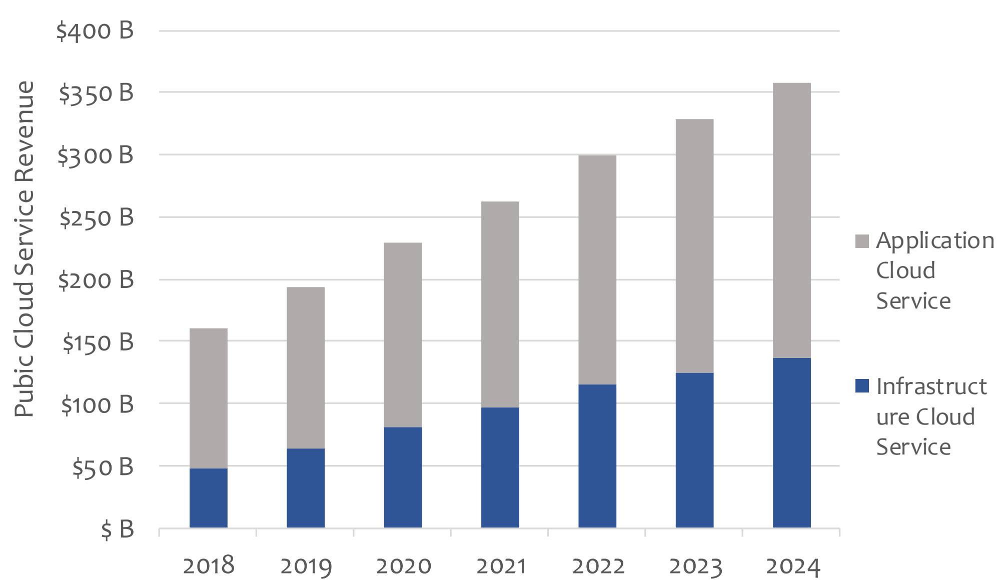
This business model is similar to the model discussed previously except that instead of a telco being the ultimate MEC service provider to enterprises, the major cloud providers like AWS, Microsoft, and Google would rent MEC infrastructure facilities including server hardware and network connectivity and offer distributed cloud computing services to the enterprises. In the cases of very large enterprises or where the 5G network is not used, this business model may be preferred.

7 Market Outlook

The Multi-Access Edge Computing (MEC) market is a subset of public cloud infrastructure services market. Here, we define the public Infrastructure Cloud Service market as the sum of Infrastructure as a Service (IaaS) and Platform as a Service (PaaS) as specified in National Institute of Standards and Technology (NIST) cloud computing definitions. In this section, Mobile Experts track the MEC service revenue opportunity by the different use cases that drive the market and provide a forecast of different MEC data center facilities by locations and by region. Also, we provide a forecast of MEC spend by hardware server and software/integration services that primarily drive the market. We further breakdown the MEC spend by region.

Public Cloud Infrastructure Revenue

The cloud computing market can be viewed as comprised of two major pieces: *Infrastructure Cloud* and *Application Cloud*. The Infrastructure Cloud is the underlying infrastructure cloud computing services whereby a customer can provision compute, storage, and networking and deploy arbitrary software application on those cloud infrastructure. The Infrastructure Cloud in our definition encompasses both IaaS and PaaS segments as defined by NIST. Examples of the Infrastructure Cloud include the major public cloud services, including AWS, Microsoft Azure, Google Cloud, and IBM Cloud. The Application Cloud is an "upper" layer—of applications that run in the cloud. Customers can access software applications on-demand such as Office 365, salesforce.com, Webex, etc. This user-level access is synonymous to SaaS as defined by NIST.



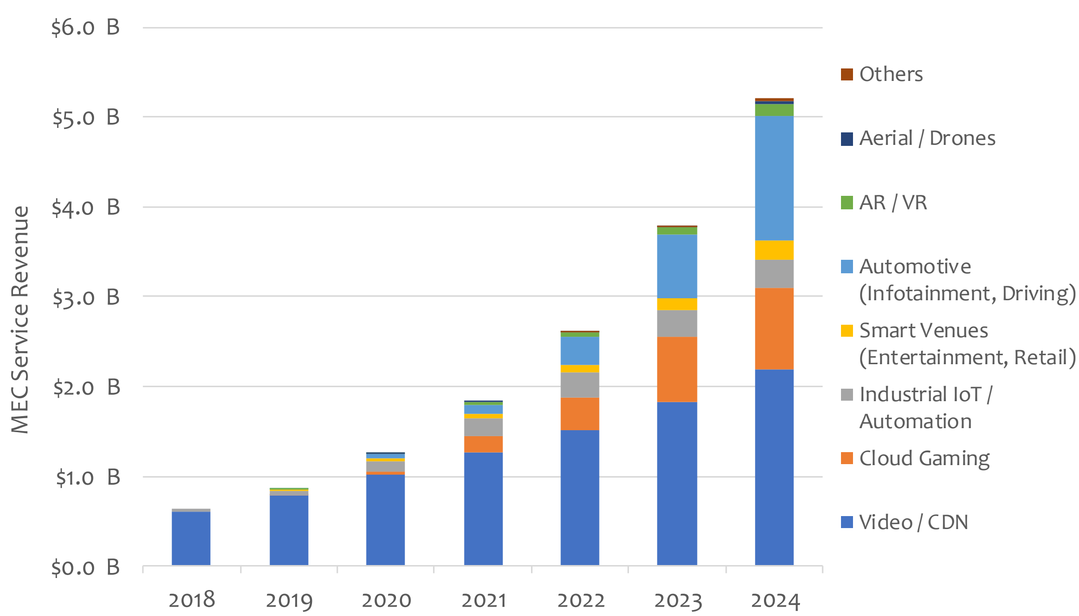
Source: Mobile Experts

Chart 2: Public Cloud Services Revenue, 2018-2024

The Infrastructure Cloud represents the underlying cloud computing environments that the major hyperscale public cloud providers like AWS, Microsoft Azure, and Google GCP enable for the overall cloud computing industry. We estimate that this segment will grow from just over $47B in 2018 to almost triple to about $140B in 2024. Fueling this growth is the continuous adoption of cloud computing by enterprises as they migrate IT spending from a full ownership model to a "cloud-first" model in which the enterprises leverage both the public and private cloud services for IT cost savings and increase business agility. While the Application Cloud segment represents the larger piece of the overall cloud computing market, this application-layer segment is somewhat orthogonal to the edge computing focus of this study.

MEC Service Revenue

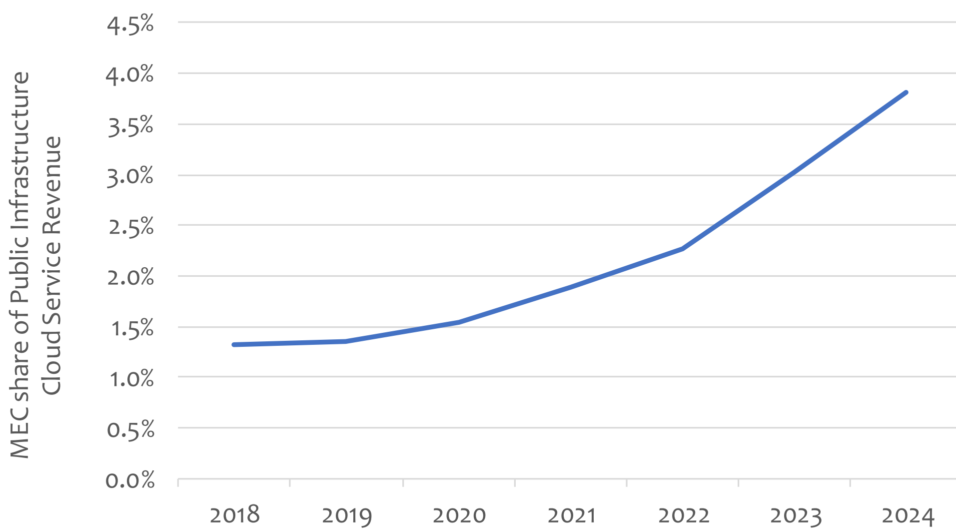
The MEC service revenue today is dominated by the traditional Content Delivery Network (CDN) video delivery services like Akamai, Limelight, and others. As the market matures and edge computing infrastructure gets deployed with faster network services, Mobile Experts projects new cloud computing services like cloud gaming, industrial IoT, and autonomous driving to significantly increase the service revenue outlook along with traditional cloud computing services related to e-commerce/retail. It should be noted that we have not captured potential MEC service revenue from Telco SDN applications like virtualized RAN as we have presumed that Telco/MNO-centric applications are assumed to be baseline drivers for telco-adoption of MEC infrastructure investments regardless of whether third-party applications will justify return-on-investment business cases.



Source: Mobile Experts

Chart 3: MEC Service Revenue by Use Case, 2018-2024

The traditional video/CDN market is arguably much higher ($8-10 billion by our estimate) than the "MEC video/CDN" service revenue reflected in the figure above. This is based on our arbitrary sub-segmentation of the traditional CDN market to highlight that a "MEC" portion of the CDN market utilizes the MEC principles of distributed, containerized microservices. We expect traditional CDNs like Akamai, Limelight, and newer entrants like Fastly, Cloudflare, and others to deploy more AWS-like cloud services, in addition to having more distributed points of presence.



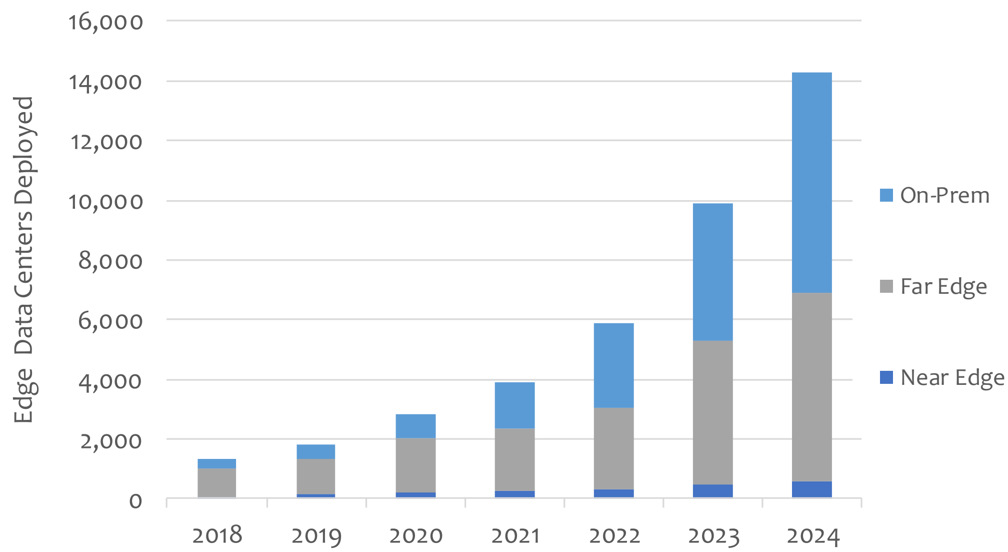
Source: Mobile Experts

Chart 4: MEC Share of Public Infrastructure Cloud, 2018-2024

While the MEC service revenue is expected to grow very quickly from under $1B in 2019 to over $5B in 2024, its share of the overall public infrastructure cloud services market is expected to remain under 4% by the end of our forecast period. While over 40% CAGR growth in MEC service revenue during our forecast period is dramatic, its mid-single-digit share of the overall public cloud infrastructure market is a testament to the overwhelming size of the overall cloud computing market opportunity at large.

MEC Data Center and Facility Outlook

While the hyperscale cloud providers like AWS, Google, Microsoft, and other major Internet companies have been deploying very large data centers around the world for their primary Internet operations and services, MEC data center or facility deployment is just getting started. The scope and scale of MEC facility deployments differ by Near Edge, Far Edge, and On-Prem installations and by region. Mobile Experts forecasts a rapid increase in MEC facility deployment from less than 1,500 in 2018 to over 15,000 in 2024 – over 50% CAGR over our forecast period.



Source: Mobile Experts

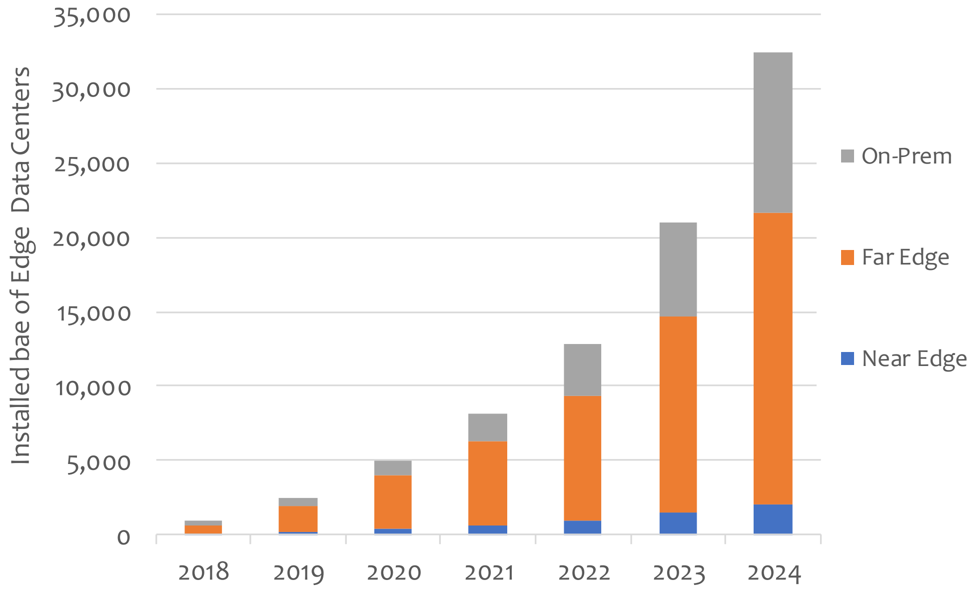
Chart 5: MEC Data Center Deployment, 2018-2024

While the number of Near Edge MEC data centers is small relative to the Far Edge and On-Prem facilities[7], the Near Edge MEC data centers will experience a faster growth (~70% CAGR growth) than the Far Edge MEC facilities (~35% CAGR growth) as most near-term edge computing use cases will not require ultra-low latency. Meanwhile, the On-Prem facilities will grow quickly (over 70% CAGR growth) from private LTE and 5G applications at enterprise locations whether the local campus network is run by the enterprise or via an operator's public network.

The Near Edge MEC data center deployments will be driven by network operators as a part of their network densification and SDN and NFV transformation. Enabling MEC data centers at a handful of aggregation sites per metro market provides an opportunity for Telcos to extend networking and computing facility to handle own network operations like C-RAN and video distribution, and extend cloud infrastructure to enterprises who seek distributed cloud nearby. For some operators--like Rakuten who is implementing virtualized RAN--the Far Edge MEC deployments will handle vRAN functions. For example, Rakuten is in the process of deploying thousands of Far Edge facilities and tens of Near Edge MEC data centers in addition to Centralized data centers for Core network and OSS/BSS functions. As private LTE and 5G networks deployed by enterprises for

[7] Please note that we refer to Near Edge MEC deployments as "data center" installations vs. Far Edge MEC deployments as "facility" installations in this report as Near Edge installations will be a few racks of servers in micro data centers while Far Edge MEC installations will likely be 1-2 servers in compact enclosures.

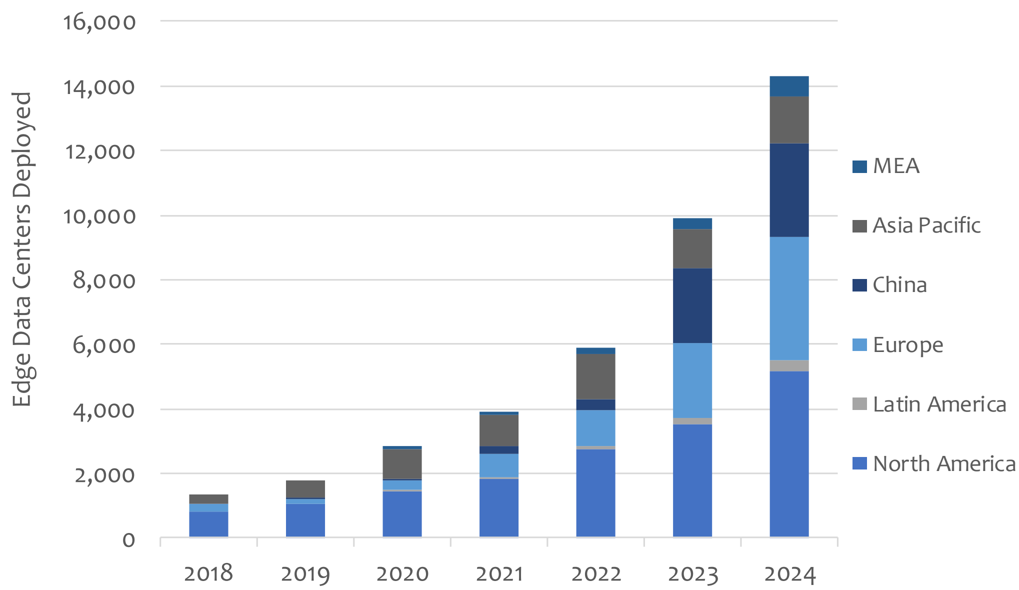
industrial IoT automation ramp-up post 2021-2022, the On-Prem MEC facility deployments will quickly increase.



Source: Mobile Experts

Chart 6: MEC Data Center Installed Base, 2018-2024

As operators and enterprise increasingly expand their data center/facility deployment out to the edge for latency-sensitive and bandwidth-intensive applications like cloud gaming and autonomous driving, etc., the installed base of Far Edge facilities will reach about 20,000 by the end of 2024. While the number of larger Near Edge MEC data centers will also expand, its installed base will be far small. The number of Near Edge MEC data centers will reach just above 2,100 globally. Lastly, the installed base of On-Prem MEC facilities will reach just under 11,000 locations, largely reflecting the number of enterprises deploying campus networks privately on their own or publicly through a network operator. For some very large enterprises, these On-Prem MEC facilities may become distributed points of presence for the cloud service providers like AWS, Microsoft, Google, and others as they continuously seek distributed points of presence.



Source: Mobile Experts

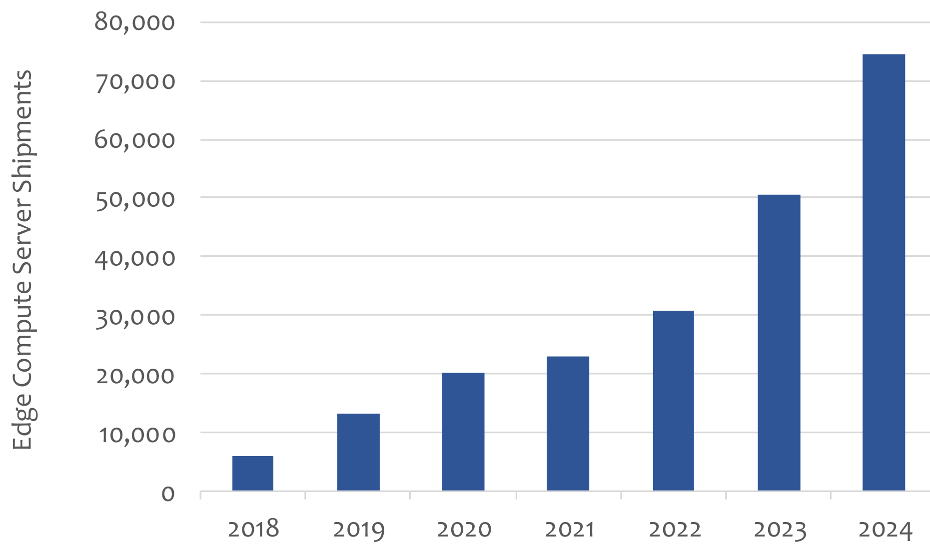
Chart 7: MEC Data Center Deployment by Region, 2018-2024

North America is expected to represent the largest market for MEC data centers or facility deployments as major fixed and mobile operators seek to transform major network aggregation sites into MEC data center or facilities. For example, the mobile operators deploying Centralized RAN architecture will transform metro aggregation sites into Near Edge MEC data centers to house commercial off-the-self (COTS) hardware for both own telco SDN operations as well as lay a foundation for third-party MEC applications. Meanwhile, the distributed cloud architecture is also being adopted by some major cable operators seeking to deploy COTS hardware for IP video delivery as more video traffic goes over IP network vs. traditional QAM-based video delivery over cable or satellite.

Europe and China are expected to represent the next largest markets for MEC data center facilities as the major operators seek to deploy distributed cloud infrastructure for internal SDN functions as well as target industrial and enterprise applications enabled through faster and more responsive 5G network capabilities. The MEC data center deployments in APAC region are heavily influenced by virtualized RAN deployment at Rakuten in Japan which is deploying tens of Near Edge and thousands of Far Edge MEC deployments. Over the longer term, we forecast automotive MEC applications like HD map download and autonomous driving to cause a significant increase in Far Edge facility deployments.

MEC Server Outlook

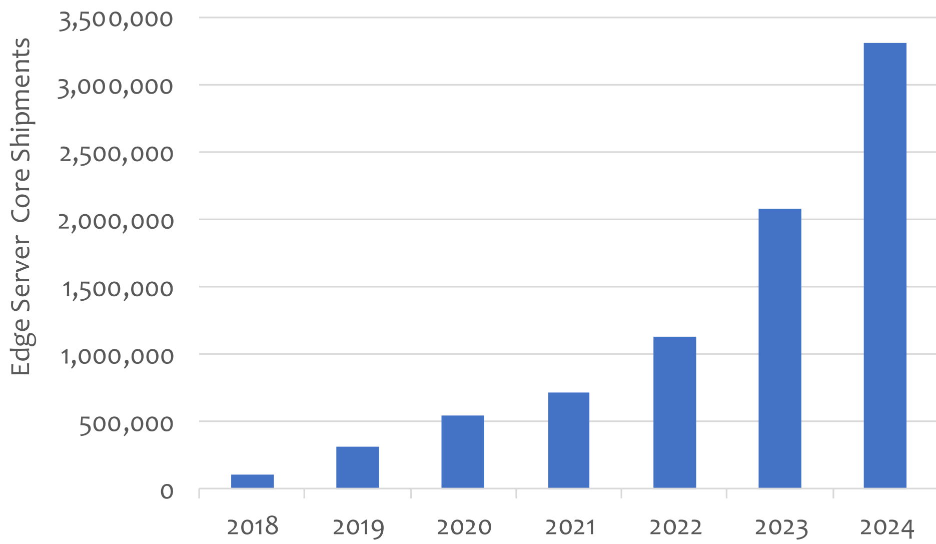
Depending on the scope of MEC data center deployments (e.g., Near Edge, Far Edge, or On-Prem), the server and core shipment will differ widely. For example, Near Edge MEC data centers will house racks of servers and a higher count of CPU and GPU cores vs. Far Edge MEC facility which will likely have a handful of servers. While the different MEC applications will require varying degrees of server capability, i.e., high vs. low number of CPU/GPU cores, we expect relatively high-end servers with 20+ cores to handle complex workloads associated with vRAN and other SDN functions.



Source: Mobile Experts

Chart 8: Edge Compute Server Deployment, 2018-2024

Based on the number of Near Edge, Far Edge, and On-Prem MEC data center or facility deployments as projected, we expect an aggregate number of server shipments to drastically increase from a couple of thousands in 2018 to almost 80,000 servers in 2024.



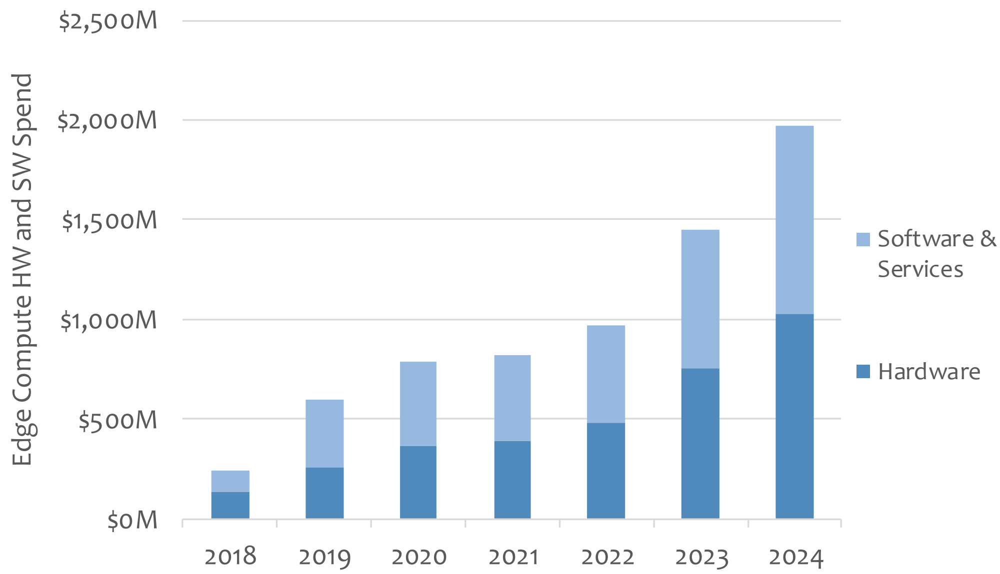
Source: Mobile Experts

Chart 9: Edge Compute Core Shipment, 2018-2024

Assuming a combination of CPU and GPU cores per server, the total number of CPU/GPU cores is expected to rise from over 100,000 cores in 2018 to about 3.5M cores in 2024. The rapid growth of core counts is a reflection of a higher number of servers and increasing core counts per server expected during our forecast period to handle myriad MEC applications – including both telco SDN functions as well as the broader scope of MEC applications in the latter half of our forecast period.

MEC Capital Expenditure Outlook

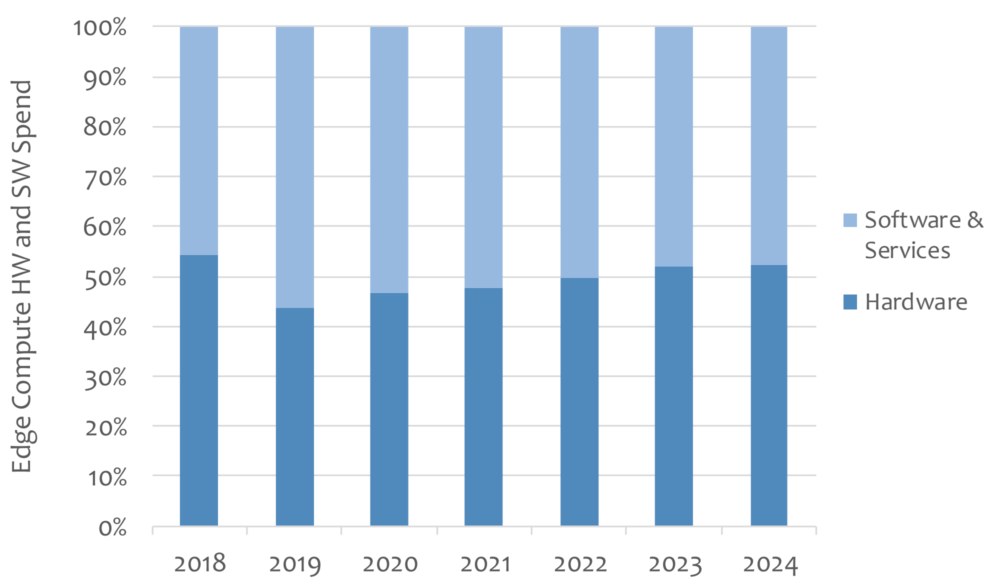
In terms of edge computing expenditure, we broadly track server/core shipments to gauge the scope of MEC infrastructure investment or spend. Based on the number of MEC data center facilities and server/core shipments associated with the edge compute facility expansion, the total MEC hardware expenditure will rise from around $130M in 2018 to over $1B in 2024 – over 40% CAGR growth.



Source: Mobile Experts

Chart 10: Edge Compute HW and SW Expenditure, 2018-2024

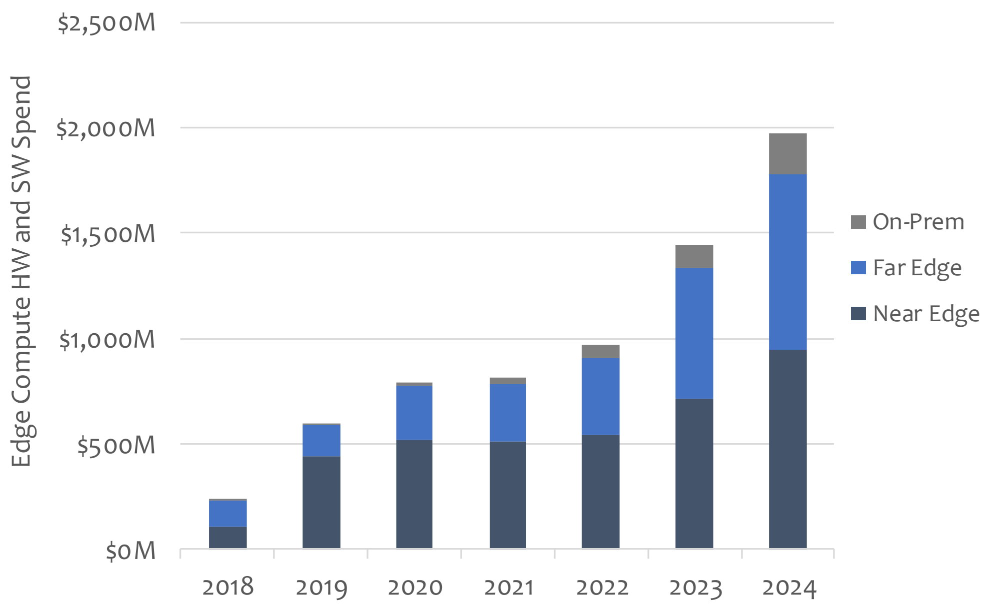
The total MEC expenditure, including hardware and software, integration, and services, is expected to rise from about $240M in 2018 to about $2B in 2024 as the operators, cloud providers, co-location infrastructure players, and enterprises invest in the distributed cloud infrastructure with MEC capabilities.



Source: Mobile Experts

Chart 11: Edge Compute HW vs. SW Share of Total Expenditure, 2018-2024

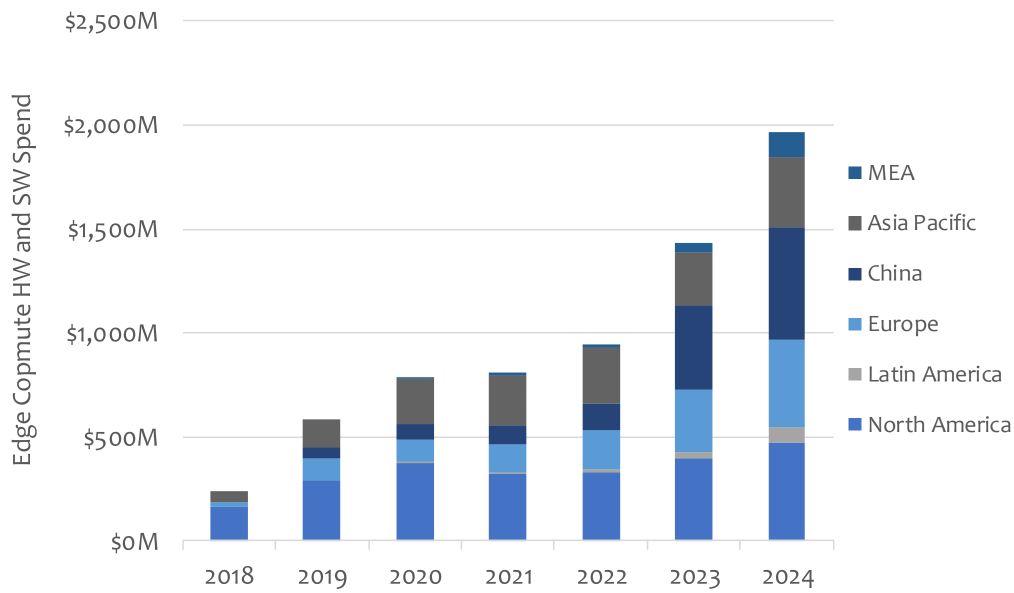
The software and services generally dominate the cost profile in the Near Edge MEC data centers due to more complex orchestration of service delivery across much larger hardware footprint, while the reverse is true in the Far Edge MEC facility. The net cost breakdown between hardware and software & services is expected to hover around 50:50 longer-term as the number of Far Edge and On-Prem MEC facilities significantly outpace that of Near Edge data centers in the second half of our forecast period.



Source: Mobile Experts

Chart 12: Edge Compute Expenditure by Location, 2018-2024

While the number of Near Edge MEC data centers is significantly less than the Far Edge and On-Prem MEC facilities (see Chart 5), the cost profile of a Near Edge MEC data center is significantly higher than that of a Far Edge or an On-Prem MEC facility. For instance, a typical Near Edge MEC data center may have 20-80 servers while a Far Edge or On-Prem facility may have 1-8 servers. Hence, the Near Edge MEC expenditure is expected to represent the biggest segment (52% share of the $2B total spend) , followed by the Far Edge MEC expenditure (39% share of the total) and the On-Prem MEC expenditure (about 1%).



Source: Mobile Experts

Chart 13: Edge Compute Expenditure by Region, 2018-2024

In terms of regional MEC spend, North America represents the largest market with over 50% share of the total MEC expenditure in the near term as fixed, cloud, and CDN operators transform their distributed cloud presences into containerized microservices. However, China combined will take a major share as operators there expand MEC for C-RAN, and other edge compute services. In 2024, China will represent about 28% of total MEC spend. Europe will represent over 21% of the total spend in 2024 as 5G, and edge computing for industrial IoT takes off in the second half of our forecast period. While the MEC expenditure associated with Rakuten's vRAN buildout in the near-term provides a meaningful boost for the APAC region, we expect a larger number of MEC deployments in Europe and China in the latter half of our forecast period to put those two regions ahead of APAC at the end of our forecast period.

8 COMPANY PROFILES

AKAMAI:

Based in Cambridge, MA, Akamai has a long history as a pioneering CDN provider. The company touts its distributed Intelligent Platform network with about 240k servers in 139 countries and nearly 1600 network locations. With the company's long history in CDN and distributed network presence, Akamai has expanded its product portfolio beyond CDN with a heavy focus on security for both network operator and enterprise customer segments.

ALIBABA:

As one of the leading Internet companies in China, Alibaba has its cloud computing offering called Aliyun (also referred to as Alibaba Cloud).   of the leading cloud providers in China with a similar business model as Amazon. According to the company website, Alibaba Cloud operates 58 availability zones in 20 regions around the world. As "Amazon of China," the Alibaba Cloud business has a similar vision and positioning as AWS. In the fourth quarter of 2018, the company reported just under $1B in cloud revenue. While not at the same scale as AWS, it has quickly grown this business in the past few years.

AMAZON WEB SERVICES (AWS):

One of the biggest Internet player in e-commerce, cloud computing, and other online retail businesses. The company pioneered the cloud computing business with its Amazon Web Services business which started "renting" its huge IT infrastructure for its primary e-commerce business. The idea of maximizing the utilization of its IT "cloud" infrastructure of servers and storage has evolved into a huge standalone AWS business which continues to grow rapidly with over $25 billion in AWS revenue in 2018. AWS is by far the dominant public cloud infrastructure provider today. The company continues to extend its cloud infrastructure through new services like Greengrass and Outpost.

AT&T:

AT&T has been public about its intention to move towards software-defined networking. As it builds out its 5G network, its Business division has been public about its intention to leverage its distributed cloud, Network Edge Compute (NEC), with cloud providers to target certain enterprise applications that need lower latency and optimized network routes. The company has identified healthcare, retail, manufacturing, and smart stadium sectors as initial target verticals. Related to this effort, AT&T has commercial trials on-going at Rush Medical Center, AT&T Stadium in Dallas, and Samsung factory in Austin.

More recently, the company has announced major cloud deals with Microsoft Azure for internal AT&T applications running via the Azure cloud and with IBM for Business focused applications. It is reasonable to expect AT&T to work with these two major public cloud providers to extend into MEC use cases.

BAIDU:

As a major Chinese Internet company, Baidu also offers cloud services like Alibaba Cloud. At CES 2019, the company announced its edge computing platform called OpenEdge. It is targeted for developers and is really a local package of its commercial offering called Baidu Intelligent Edge (BIE). Baidu has been active in Linux Foundation open source projects and appears to be packaging some of the open-source projects as a baseline for its cloud service offerings.

BASELAYER:

BaseLayer was spun out of the IO company split in 2015 as a "technology" portion of the IO and the remainder IO being the data center infrastructure company providing space and power. BaseLayer provides different "modules" which are basically full-featured data centers in different form factor similar to shipping containers. In addition to "Core" class modules, the company provides "Edge" modules ranging from 50 kW to 500 kW of IT capacity. The company touts very compact and dense data center capacity that can be placed in edge locations.

CHINA MOBILE:

China Mobile has several edge computing projects in progress to evaluate technical feasibility and business case. The use cases are wide-ranging from smart city video networking (Alibaba, Inspur, and Tridium), construction (China Construction Group), smart manufacturing (Huawei, Advantech, Ericsson, NXP, and Lenovo), CDN (Tencent), 5G gaming (internal), 360-degree VR video broadcasting (Intel), 12k panoramic VR video-on-demand (internal), and automotive (Baidu). These projects will be evaluated on 100 "edge computing ready" locations.

CHINA TELECOM:

China Telecom is targeting to build a cloud-based network with the implication that MEC will be an important aspect of this vision. While the operator has laid out its vision to deploy computing, storage, and service capabilities at the network edge to realize distributed development of applications and services that run on its cloud-based network, public information about specific details of its MEC trials are missing.

China Unicom:

Like other Chinese operators, China Unicom has been experimenting with mobile edge computing use cases along with its vendor partners and three major cloud providers in China: Alibaba, Baidu, and Tencent. More recently, China Unicom, Baicells, and Artesyn worked on a joint R&D project to apply MEC and 5G for live panoramic VR solutions using drones. China Unicom is exploring other MEC and 5G use cases, including smart campus and stadium venues, industrial IoT, and V2X.

Cisco:

As a leading networking company, Cisco has a wide range of network equipment solutions for both service providers and enterprises. Cisco has been working very closely with Rakuten to help build out Rakuten's mobile network on the virtualized network. Cisco is providing Mobile Core and other key network components in Rakuten's NFVI platform.

CloudFlare:

Based in San Francisco, CloudFlare provides a multitude of services including "security as a service," CDN, DDOS mitigation, web-based application firewall, DNS, etc. Similar to other CDN players, CloudFlare operates distributed network of servers to provide its cloud services. The company operates in 151 data centers in 180 cities around the world. The company recently raised $150M (Series E) funding round in March 2019 to continue its expansion.

DartPoints:

Based in Dallas, Texas, DartPoints is one of many micro data center companies looking to establish edge data center locations for private colocation facilities for edge computing. The company has announced plans to branch out into several US cities including NY area, Phoenix, Las Vegas, St. Paul, Minn., and Kansas City. The company plans to deploy its micro data center facilities in 100 kW increments.

Dell / EMC:

Dell is the market leader in server hardware. In addition to its leading position in servers, its EMC business provides a strong market position in storage along with VMware on virtualization. Hence, the company is able to provide an integrated or converged server solution from hardware to the virtualization software stack for cloud deployment.

Deutsche Telekom:

As one of the major network operators in the world, Deutsche Telekom has been looking into the possibility of mobile edge computing and 5G for many years. The company sees many possibilities and has spun-out its mobile edge computing R&D as an independent edge computing company, MobiledgeX. The company is reported to have MobiledgeX platform running in 5 MEC centers and expect to have possibly 10-12 location by the end of 2019. According to a MobiledgeX executive, depending on business case and applications, the operator may deploy hundreds of these MEC centers in the future.

Digital Bridge:

Digital Bridge is both a tower and a data center company which owns two data center companies (DataBank and Vantage Data Centers) and operates hundreds of thousands of cell sites in the USA and Latin America. In partnership with the private equity firm, Colony Capital, and teaming with an investment fund, the company has announced a deal to acquire Zayo to expand fiber and data center portfolio. As a major data center and tower infrastructure company, it will likely become a major player in edge computing as the economics and business models become more firmed up.

EdgeConneX:

EdgeConneX is a neutral host data center provider with footprints in North America, Europe, and South America. The company touts a global footprint across over 30 metro markets. The company provides customizable data center capacity ranging from 100 kW to 100 MW facilities depending on customer needs. For example, the company has two data center facilities in Chicago – 20MW and 6MW facilities.

EdgeMicro:

EdgeMicro is an edge colocation company launched in 2017 dedicated to delivering on the promise of edge computing. EdgeMicro plans to deploy hundreds of network-neutral, modular "micro" data centers at the edge and has announced a plan to deploy three micro data centers in Austin, Raleigh, and Tampa, based on its proof-of-concept data center in Denver.

Equinix:

As one of the leaders in data center infrastructure services, Equinix is increasingly layering on cloud infrastructure services on top of its co-location offering. In addition to Equinix Cloud Exchange Fabric, which provides network connections between data center to data center on demand, the company announced Equinix Network Edge that allows customers to launch virtual network services like load balancing, firewall, etc., without needing extra hardware. Equinix Network Edge along with Cloud Exchange Fabric are an example of ways in which the data center infrastructure company is going up the stack to cloud infrastructure services.

ERICSSON:

Ericsson's Distributed Cloud Infrastructure provides open and standards-based solutions, including NFVI solutions for data centers, edge, and deep edge facilities. Ericsson provides its Cloud Infrastructure solution through a business group called Edge Gravity, comprised of hardware, software, and services to 140 customers worldwide, of which 85 customers have gone live. Ericsson has launched its Edge NFVI solution targeting Near Edge deployments and has launched a VNF Certification program to standardize on testing with partner VNFs to harden integrated solution for customers. Ericsson recently announced its proof-of-concept trial of deploying a Core EPC function as a cloud-native microservices in a live Verizon network.

FASTLY:

Fastly is a relatively new comer to the CDN industry. Founded in 2011 and based in San Francisco, the company bills itself as providing a new edge cloud platform based on latest cloud technologies such as containerized microservices running on virtualized infrastructure. With more localized handling of traffic at 60 "uniquely designed" edge points of presence, some workloads can be handled locally versus sending all the way to centralized CDNs like AW CloudFront and similar offerings from Microsoft Azure. The company recently went public IPO raising prospects of similar cloud-centric CDN providers like CloudFlare and others.

GOOGLE:

Google GCP is one of the hyperscale cloud providers – along with AWS and Microsoft Azure. While the majority of its cloud capacity in 60+ availability zones and 20 regions worldwide is utilized for its core services like Google Search, Youtube, Google Maps, etc., some of that cloud computing resources are utilized for GCP services to outside companies. For edge computing, the company notes that 2-3 edge locations per metro market are typical, although some can go as high as 8 edge locations. To meet the enterprise demand for hybrid cloud, Google offers GKE On-Prem service to run Kubernetes cloud engine on servers on-premise.

HUAWEI TECHNOLOGIES:

As the leading networking vendor in China, Huawei has been very active in operator adoption of NFVI in Core networking and is working closely with the Chinese operators as they explore pushing network virtualization out to the edge. According to the company, it has 20 proof-of-concept and commercial MEC deployments and has seen 30% latency reduction in MEC deployments. It is collaborating with 30 developers on various MEC implementations. In addition to its work in NFV software and server hardware, the company introduced its ARM-based server CPU based on 7nm processing technology in early 2019.

IBM:

IBM has been building its cloud computing business through a series of acquisition over the past few years. It acquired SoftLayer in 2013 to bolster its cloud data center infrastructure; bought RedHat for its open, multi-cloud platform. By combining physical infrastructure (SoftLayer) and software, integration, & services (RedHat), the company is positioning itself to serve large enterprises adopting the hybrid cloud strategy leveraging both public and private cloud services.

INTEL:

Intel's x86 CPU chipsets dominate in data center server deployments. While some specific workloads may require GPU or FPGA acceleration in combination with CPU, most server software and workloads heavily use x86 CPU. As a result, Intel is an important component supplier to the data center server market. As edge computing server deployments ramp up and cloud services increasingly leverage those edge compute facilities, Intel is expected to benefit. In addition to general enterprise and data center applications leveraging x86 CPU, the company also provides x86 CPU plus FPGA acceleration solution for some Telco workloads like vRAN. The company is working actively in O-RAN and other NFV initiatives which will certainly benefit its Data Center business.

KOREA TELECOM (KT):

KT has already launched its 5G network along with other major operators in Korea. Coinciding with its 5G network launch, KT has completed the construction of MEC centers in 8 major cities to help boost network performance. The operator reports that it has applied control and user plane separation (CUPS) architecture and running network function in a virtualized environment at those MEC centers.

Limelight:

Limelight is another major CDN service provider with more than 100 points of presence with direct connections to over 1000 ISPs. Although its primary business is in CDN and video delivery, it has expanded cloud service offerings into security and web performance as the CDN market has been commoditized by the hyperscale cloud providers who have much extensive cloud computing capacity than niche CDN players like Akamai and Limelight.

Microsoft (Azure):

Microsoft has transformed its server and application software businesses to the cloud. Its Azure cloud service offering is second to AWS and is gaining momentum among retail customers who are weary of running their e-commerce businesses on a competitor's platform, AWS. In addition to the Azure Cloud, which provides IaaS and PaaS services, Microsoft also provides many SaaS offerings, including Office 365, Linkedin, Skype, etc. The company has won several large Telco wins including its most recent deal with AT&T, SKT, and others. With the company's strong heritage and relationships with enterprises and business application developers, some key operators looking to enable edge computing with 5G are looking to establish a partnership with Microsoft Azure.

MobiledgeX:

MobiledgeX was spun-out from Deutsche Telekom as an independent mobile edge computing company with a goal to build a marketplace of edge resources and services. The company aims to connect developers with mobile networks for next-generation of mobile edge computing applications and services through "cloudlets," which are containerized NFVI that provide standardization and secure resource allocation to operators and developers. The company offers SDK and API to dynamically place application backends. The company has trials with DT (in Germany), SKT (Korea), and Telus (Canada).

Nokia:

As a major infrastructure vendor to telecom operators worldwide, Nokia has been working with operators on edge computing for many years. Nokia offers hardware server and distributed cloud software implementation under its AirFrame Open Edge server with OpenStack distribution. Nokia sees edge computing opportunities in the context of numerous private LTE and 5G use cases and continues to be involved in trials.

NTT DOCOMO:

NTT Docomo is Japan's largest mobile operator. NTT's private cloud called Docomo Cloud Platform (DCP) has grown over the years since its beginning in 2015. As of the end of 2018, DCP has 200k cores of compute capacity across 11 regions. As the operator builds out its 5G network, the DCP is expected to expand further into distributed sites and leverage container technologies like Akraino to extend Kubernetes onto its OpenStack virtualized platform. NTT launched "5G Open Cloud" program to innovate on new use cases on the 5G network. The program has been joined by 1600 companies and organizations.

ORACLE:

While a latecomer to cloud computing, Oracle has been touting its "cloud-native" Oracle Cloud platform based on open standard technologies such as Kubernetes, Docker container, etc. Oracle offers 5G Core network functions that can run on virtualized network infrastructure. It is not clear how those VNFs may interoperate in a MEC context.

ORANGE:

Orange has been taking a more cautious approach to 5G and edge computing. With respect to mobile edge computing, the operator is working with Renault and Ericsson on connected car 5G trial. The trial will test hybrid V2X (vehicle to infrastructure or another vehicle) system under Network Slicing and MEC to see how much system performance can be improved through the distributed cloud infrastructure.

ORI:

Ori is a London-based edge computing startup that aims to enable developers to deploy edge applications on mobile networks. Ori's DNA platform creates a virtual service layer across multiple operator networks so that developers can specify locations, and the platform would automatically deploy that application at right end points. The company has received a seed funding from a network operator.

PACKET:

Packet is a leading bare metal cloud for developers. Its proprietary technology automates physical servers and networks without the use of virtualization or multi-tenancy – powering over 60k deployments each month in its 18+ global datacenters. Founded in 2014 and based in New York City, Packet provides public cloud service in "private deployment" model which enables companies to automate their own infrastructure in facilities all over the world. Packet uses Open19 design that facilitates faster deployments.

QUANTA CLOUD TECHNOLOGY:

As one of the leading ODMs in Taiwan, Quanta Cloud Technology (QCT) supplies a broad array of server products to the cloud computing industry. Under its brand name organization, QCT provides server equipment to telecom industry segment and has high hopes of expanding into enterprises looking to expand 5G-related investments.

RAFAY SYSTEMS:

Rafay Systems enables performance improvements for SaaS applications. Rafay's Programmable Edge platform based on Kubernetes provides developer tools to automatically deploy performance and location-sensitive micro-services closer to endpoints. With a presence at the infrastructure edge, Rafay's platform improves end user experiences.

RAKUTEN:

Rakuten is a major e-commerce retailer in Japan and also offers mobile service through MVNO arrangements. The company has recently been granted 5G spectrum licenses, and is in the process of building out a virtualized mobile network. The company is building out tens of regional data centers along with Far Edge MEC facilities to handle vRAN implementation. It is working closely with Cisco, Nokia, Alitostar, and others in building out its 4G and 5G network.

SAGUNA NETWORKS:

Based in Israel, Saguna has been a pioneer in mobile edge computing, starting to implement ETSI MEC compliant MEC solution. The company has conducted a trial test with Vodafone showcasing the benefits of MEC in video delivery over the mobile network. The trial tested video streaming quality over MEC using Saguna Networks vs. virtual video server running in AWS. The trial showed improved user experience through faster start times, less wait time for re-buffering, and reduced video stalls.

SAMSUNG:

While Samsung has a portfolio of RAN products for LTE and 5G, its mobile edge computing solution portfolio is largely based on partnerships and OEM arrangement with server hardware vendors. For mobile edge computing segment, Samsung has invested in Packet through its innovation and venture group, Samsung Next.

SK TELECOM (SKT):

As the largest mobile operator in Korea, SK Telecom has launched two MEC centers in relation to its 5G network launch. The company has signed an MoU in recent months to collaborate on IoT business in smart factory, AI technologies and services, and media and entertainment services.

SPRINT:

Sprint Business is leveraging distributed micro data centers for its Curiosity IoT business. The operator touts (<5kW) micro-edge pops to deliver Core round-trip latency between 2-10 ms. Through these MEC facilities, the operator claims that the distance from the sensor to applications can be reduced from 1000 miles to less than 50 miles, reducing the latency to below 20ms. The operator has worked with Softbank and Packet to build the Curiosity IoT platform.

STACKPATH:

Based in Dallas, Texas, StackPath bills itself as having invented edge computing. The company is started by a SoftLayer founder after selling the company to IBM in 2013. StackPath touts 45 edge locations connected with the private network backbone. The company offers edge computing VMs and containers and emphasizes security in network traffic controls and offers edge services including CDN, DNS, WAF, monitoring, and more. Based on its press release, it reported $200M annual run-rate revenue back in 2018.

TELEFONICA:

Telefonica's edge computing initiative is based on its UNICA program, which encompassed network virtualization initiatives many years back. As its network virtualization extends from Core to access networks, it has started its UNICA EDGE program which aims to identify MEC locations where fixed and mobile services can be converged. According to one of its executives, a few hundred locations can be possibly be transformed into edge cloud locations out of 6000 or so central offices in its footprint in Spain.

VAPOR IO:

Vapor IO is building a neutral-hosted cloud by delivering a suite of hardware and software for edge computing and operating edge colocation services. The company's technology enables highly-distributed micro data centers to be embedded in the wireless and wireline infrastructure, colocated with the last mile or Radio Access Network and meshed together with software and high-speed fiber as part of the company's Kinetic Edge, technical architecture for city-scale edge computing.

VASONA NETWORKS (ZEPHYRTEL):

Vasona Networks provides mobile edge computing software for RAN capacity optimization. The company touts that its MEC software for RAN optimization has been deployed in 150,000 3G and LTE cells. The company was acquired by ZephyrTel in late 2018. ZephyrTel, which itself was formed in early 2018 through several portfolio company acquisitions, aims to help telcos capitalize on the benefits of the cloud.

VERIZON:

Verizon views mobile edge computing as one of the key pillars of its 5G network strategy. The operator has announced that it will have its first MEC center online by the end of this year. Verizon's mobile edge computing resides on what it calls "Intelligent Edge Network" (iEN). It is generally acknowledged that some of the C-RAN hub sites can host MEC servers to handle run edge applications that need lower latency and other performance requirements. It is reported that Verizon is testing cloud gaming service using MEC whereby games are hosted in the cloud rather than on consoles. CDN/video delivery will likely be another application of MEC as Verizon expands its access network capacity.

WIWYNN:

Based in Taiwan, WiWynn was founded in 2012 with a vision of being a hardware manufacturing partner to cloud service providers (e.g., Amazon, Google, etc.). With backing from a leading computer ODM, Wistron, the company began operation manufacturing workload-optimized servers to very large cloud providers who have specific workloads and look to optimize for a total cost of ownership looking at ways to cut costs in power consumption, space, etc. As one of the leading ODMs in the data center server space, it may become an ODM partner in edge computing, but the highvolume scale will ultimately determine whether a company like Wiwynn will become a partner.

ZTE:

As a major telecom vendor in China, ZTE has conducted many edge compute trials with operators and other partners. ZTE offers a MEC server based on a dual-socket Intel Xeon CPU. The company has announced a partnership with Tencent to promote the application of edge computing and 5G networks. The company has indicated that it will invest more than 10% of its sales revenue on R&D, focusing on 5G chipset development and edge computing.

9 ACRONYMS

5G NR: 5G New Radio (a global 5G air interface standard)

AF: Application Function (one of many components in 5G Core)

AR: Augmented Reality

AWS: Amazon Web Services (a pioneering and leading hyperscale cloud provider)

CAPEX: Capital Expenditure

CDN: Content Delivery Network

CO: Central Office

CORD: Central Office Re-architected as Data Center

COTS: Commercial Off-the-Shelf (a reference to "white box" servers and switches)

CPE: Customer Premise Equipment

CPU: Central Processing Unit (typically referring to the x86 processor)

C-RAN: Centralized or Clod Radio Access Network

CSP: Cloud Service Providers (typically referring to very large webscale players like AWS, Microsoft Azure, Google Cloud Platform)

CUPS: Control and User Plane Separation

DC: Data Center

DDoS: Distributed Denial of Service

DNS: Domain Name Service

ETSI: European Telecommunications Standards Institute

GB: Gigabyte (of memory)

GCP: Google Cloud Platform (a reference to Google's public cloud service)

GDPR: General Data Protection Regulation (European regulation)

GKE: Google Kubernetes Engine

GPU: Graphical Processing Unit

IaaS: Infrastructure as a Service

IoT: Internet of Things

IP: Internet Protocol

ISP: Internet Service Provider

IT: Information Technology

LF Edge: Linux Foundation Edge (a set of open-source MEC projects)

LTE: Long Term Evolution (a reference to 4G air interface standard)

MANO: Management and Network Orchestration

MEC: Multi-Access Edge Computing (formerly Mobile Edge Computing)

MNO: Mobile Network Operator

MSO: Multiple System Operator (a reference to cable operators)

NEBS: Network Equipment Building System (environmental hardware certification)

NFV: Network Function Virtualization

NFVI: Network Function Virtualization Infrastructure

NIST: National Institute of Standards and Technology

ODM: Original Design Manufacturer (often refer to "white box" manufacturers)

OEM: Original Equipment Manufacturer

ONAP: Open Networking Automation Platform

OPEX: Operational Expenditure

OPNFV: Open Platform for NFV

O-RAN: Open RAN (Alliance)

OTT: Ove-the-Top (service provider)

PaaS: Platform as a Service

QAM: Quadrature Amplitude Modulation

QoE: Quality of Experience

QoS: Quality of Service

RAN: Radio Access Network

RU: Radio Unit (in Open RAN context)

SaaS: Software as a Service

SDK: Software Development Kit

SDN: Software Defined Network

SoC: System on a Chip

TIP: Telecom Infra Project

UE: User Equipment

UPF: User Plane Function (one of many components in 5G Core)

URLLC: Ultra Reliable Low Latency Communications

V2X: Vehicle to anything (vehicle to vehicle and vehicle to infrastructure)

VM: Virtual Machine

VNF: Virtualized Network Function

VR: Virtual Reality

vRAN: Virtualized Radio Access Network

WAF: Web Application Firewall

WAN: Wide Area Network

10 METHODOLOGY

To create estimates and forecasts for MEC service revenue, MEC deployments, and MEC HW and SW spend, Mobile Experts relied on direct input from more than 20 industry sources, with communication service providers, edge compute software vendors, server hardware vendors, and some enterprise IT companies. Mobile Experts built a "bottom-up" forecast based on public announcements from mobile operators and edge infrastructure companies. For MEC service revenue forecast, Mobile Experts built a "top-down" forecast based on trends in various use cases identified and general enterprise adoption trend of cloud computing model for technology consumption.

Infrastructure Cloud Service	Infrastructure as a Service (IaaS) and Platform as a Service (PaaS) combined. As hyperscale cloud service providers increasingly gain scale, traditionally separated IaaS and PaaS services are offered as an underlying infratructure cloud service.
Application Cloud Service	Applications consumed as a service. Often refer to as "Software as a Service" (SaaS).

Source: Mobile Experts

Figure 22. Public Cloud Service Definitions

Video / CDN	Video processing, caching, or analytics of higher-resolution video streams and delivery. Online video streaming CDN by fixedline providers like cable operators are included.
Cloud Gaming	Gaming delivered over the cloud so that users can play online games on different devices. Enterprise opportunity arises from working with gaming or hyperscale cloud providers like AWS, Azure and Google Cloud Platform to deliver to real-time mobile games at scale
Industrial IoT	Industrial automation applications in smart factory, utilities, mining and construction verticals
Retail / E-commerce	E-commerce use cases to expedite e-commerce via mobile and fixed devices
Automotive (Infotainment/ Driving)	Automotive applications related to safety, vehicle infotainment, HD mapping, navigation, and autonomous driving
AR / VR	Augmented and virtual reality applicartions via goggles for enterprise applications like training, real-time diagnostics, and AI-powered assistance.
Aerial / Drones	Drone and other aerial applications for navigation or autonomous flying

Source: Mobile Experts

Figure 23. MEC Use Case Definitions

Near Edge Data Center	MEC edge cloud location located in metro area (20-40 servers per site)
Far Edge Data Center	MEC edge cloud location closer to RAN aggregation sites (4-6 servers per site)
On-Prem Data Center	MEC edge cloud location resides on-site at enterprise locations (1-2 servers per site)

Source: Mobile Experts

Figure 24. MEC Data Center (Location) Definitions

HW Server	typically x86 Server + Memory + Storage + Connectivity
Software Integration & Services	Most of the software stack cost is associated with the cost of integrating open source software stacks as well as some customization and optimization work on that software

Source: Mobile Experts

Figure 25. MEC Cost Element Definitions

North America:	USA and Canada
Latin America:	Mexico through South America, including Caribbean
Europe:	Western and Eastern Europe, including Russia
China:	China, including Tibet and Hong Kong
Asia Pacific:	India through Australia/Micronesia, excluding China
Middle East/Africa:	Pakistan and Turkey through Africa

Source: Mobile Experts

Figure 26. Geographic Regions